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THE UNIVERSITY OF ALBERTA

# Modelling and Optimization of Coal Preparation

by

© D.L. Romero

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF Master of Science

IN

Mineral Engineering

Department of Mining, Metallurgical and Petroleum

Engineering

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Fall 1987

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled Modelling and Optimization of Coal Preparation submitted by D.L. Romero in partial fulfilment of the requirements for the degree of Master of Science in Mineral Engineering.

.....
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.....

.....

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# DEDICATION

To Joy.

## ABSTRACT

Plant trials were carried out at the Line Creek coal preparation plant, with individual coal seams, to characterize their behaviour through the cleaning circuit. For each seam:

- an empirical model was derived that allows determination of heavy media circuit yield, given the raw and clean coal ashes,
- a constant yield and quality component was determined for the water-only cyclone and flotation circuit.

A simulator was developed which gives overall plant yield and clean coal ash results for the full range of heavy media cut-points for any blend of seams in the feed and at any level of raw coal ash for each seam. The simulator can also recommend an optimal seam blend for a given supply of raw coals such that yield is maximized while satisfying all clean coal quality and raw coal utilization constraints.

Good agreement was found between "plant reported" and "simulator predicted" results. Use of the simulator has resulted in:

- a significant reduction in the variation of clean coal ash results,
- an incremental plant yield increase,
- more effective use of available raw coals.

## ACKNOWLEDGEMENTS

The author would like to thank the management of Crows Nest Resources Limited for allowing this work to proceed. Special thanks must go to Mr. John Van den Broek (Manager, Plant) for his constant guidance, support, and patience during the course of this study; and to Professors Plitt and Flintoff for their help in completing this thesis, under rather unusual circumstances.

Special thanks must also go to Mr. Anthony Timmons (Quality Supervisor) and to Mr. Ronald Kostiuk (Senior Analyst) for their outstanding efforts during the sampling campaigns and the subsequent analyses of the many samples generated.

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# 1. INTRODUCTION

## 1.1 FOREWORD

In general terms the practice of coal beneficiation involves lowering the level of impurities, usually ash and sulfur, in a raw coal to the point where customer specifications are met. When this is accomplished in the most productive and cost effective manner, the practice stops being an art and must be considered a science. This science is known as plant optimization. It begins with the earliest stages of flowsheet design and continues for the life of the operation.

Sulfur is not a problem in western Canadian coals, typical contents being less than one percent (1). Ash is the impurity that must be reduced to acceptable levels. For metallurgical coals this level is from 7.0 to 9.5 percent and thermal coals are typically below 16 percent.

In the past six years we have seen a drastic change in the character of the world coal market, and this has had a tremendous impact on the western Canadian coal industry. The world supply of coal (metallurgical and thermal) greatly outweighs demand and, as a consequence, prices have seriously eroded. The scene has changed from high production and expansion to cutthroat competition and ever-decreasing prices.

It is the opinion of the author that this downward trend will continue over the next few years and that demand

will not catch up to supply until well into the next decade. It is against this somber backdrop that the field of plant optimization will be examined, since in the face of industry extinction the science of coal beneficiation is an imperative.

## 1.2 THE INDUSTRY IN WESTERN CANADA

Western Canadian coals exhibit some rather difficult processing and handling characteristics; a direct result of the extreme geological disturbances that formed the Rocky Mountains. Tremendous shear forces extensively fractured the coal seams. As a result these coals are very friable and easily degrade during mining. Fines contents in the range of 35 to 40 percent minus 0.5 mm are not uncommon. Since processing and drying costs increase quite rapidly with increasing fines, these coals pose quite a challenge to the process engineer. Because of their tendency to generate dust during handling (2), proper design of material transfer points and the careful selection of dust control equipment are essential.

The typical western Canadian coal preparation plant for metallurgical coal separates the feed at 0.5 mm. The coarse fraction which can have a top size of 50 mm is handled in heavy media cyclones (some utilize a heavy media bath for the very coarse fraction, thus leaving a much narrower size range for the heavy media cyclones). The fines are processed in water-only cyclones (one plant sends its fines directly

to flotation). The clean coal product from the water-only circuit is usually screened at 0.25 mm and the undersize is further upgraded through flotation. The products from the coarse and fine circuits are then transported via a common conveyor belt to a fluidized bed dryer where the moisture content is lowered to an acceptable level, typically 8 percent or less (refer to Figure 1.1).

Operators will always endeavour to achieve the required level of cleaning at the highest possible clean coal yield. However, this is usually done on the basis of past experience without a clear understanding of what is happening in each constituent circuit. This is, therefore, fertile ground in which to reap the benefits of plant optimization.

## 1.3 THE LINE CREEK COAL PREPARATION FACILITIES

The Line Creek Mine is operated by Crows Nest Resources Limited, a wholly owned susidiary of Shell Canada Resources Limited. It is located approximately 25 km north of Sparwood in southeast British Columbia, Canada (refer to Figure 1.2). The Line Creek coal deposit is part of the Upper Elk Coalfield in the East Kootenays. The coal is a medium volatile, low sulfur, bituminous coal and is used as a coking coal. Coal close to the outcrop is typically of low Free Swelling Index (F. S. I.) and is processed for thermal use. Typical specifications for metallurgical and thermal coal products are given in Table 1.1 (3).

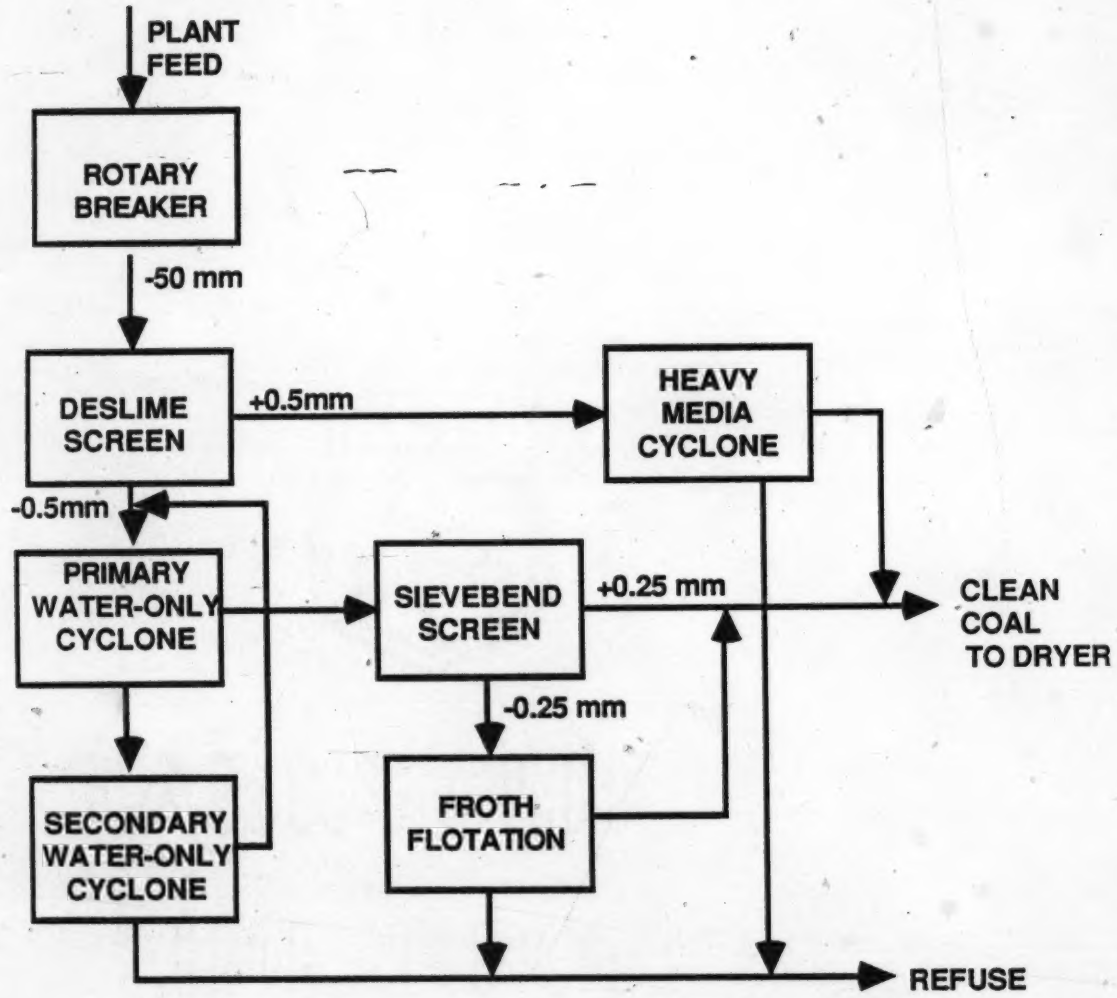



Figure 1.1 Typical Flowsheet of a Metallurgical Coal Preparation Plant.

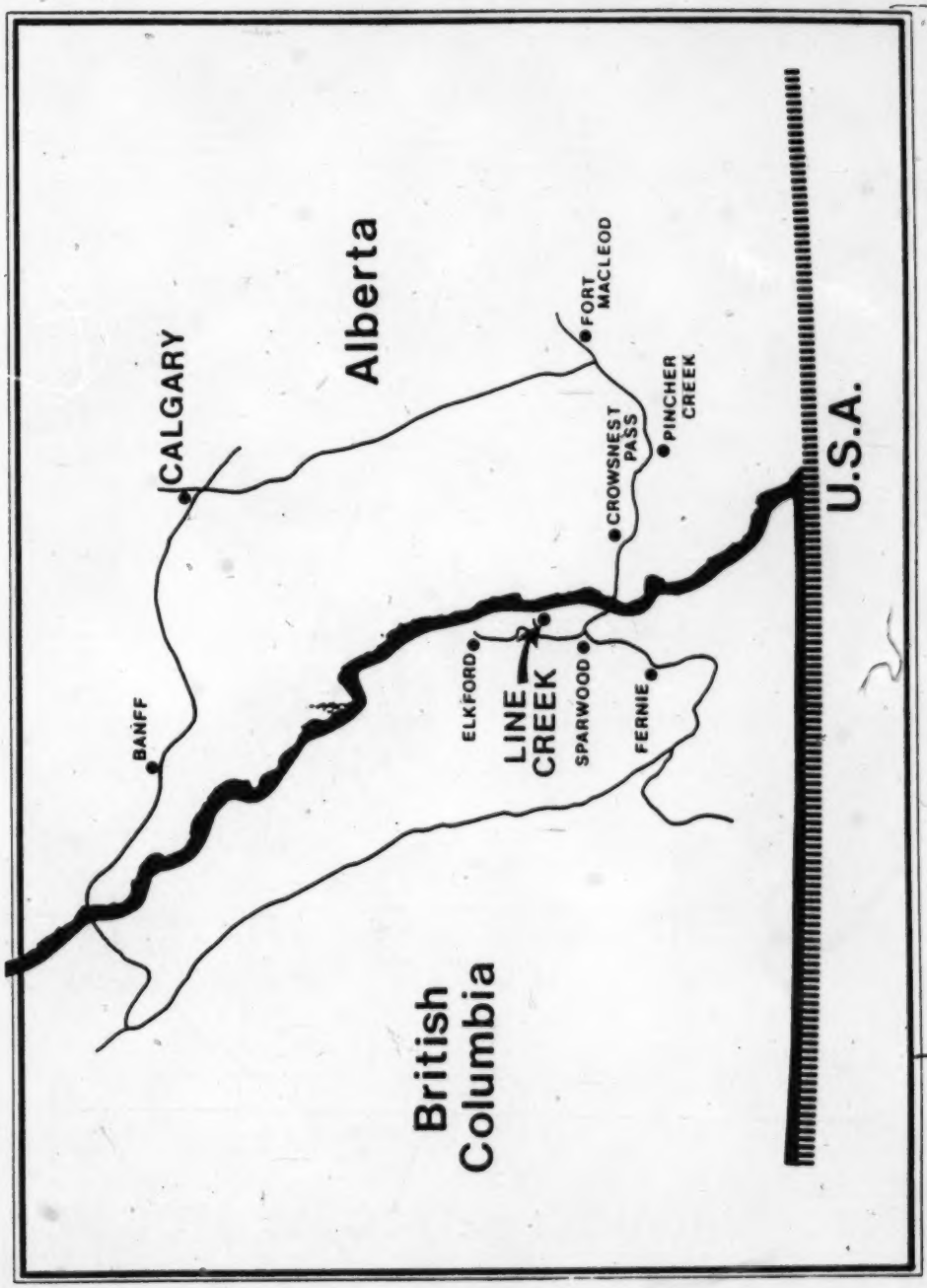



Figure 1.2 The Geographical Location of the Line Creek Mine

Table 1.1 Typical Metallurgical and Thermal Coal Product Specifications

| | BASIS | THERMAL COAL | METALLURGICAL COAL |
|---|---|---|---|
| Total moisture | % A.R. | 7.0 - 8.0 | 7.0 - 8.0 |
| Residual moisture | % A.D. | 0.8 - 1.2 | 0.8 - 1.2 |
| Ash | % A.D. | 15.0 - 17.0 | 9.5 |
| Volatile matter | % A.D. | 20.5 - 21.5 | 21.0 - 22.0 |
| Ultimate Analyses | % D.A.F. | | |
| Carbon | | 85.85 | 85.85 |
| Hydrogen | | 4.67 | 4.67 |
| Nitrogen | | 1.10 | 1.10 |
| Sulfur | | 0.37 | 0.37 |
| Oxygen | | 8.01 | 8.01 |
| Gross calorific value | cal/g. A.D. | 6,700 - 6,900 | 7,700 |
| Hardgrove grindability index | | 75.0 | 75.0 |
| Ash fusion temp. | °C | 1,450.0 | 1,450.0 |
| Size | mm | 0 - 50 | 0 - 50 |
| F.S.I. | | - | 5 - 7 |
| Maximum gieseler fluidity | D.D.P.M. | - | 10.0 |
| Total dilatation | | - | 10.0 |
| Coke strength | | | |
| ASTM stability | | - | 53.0 |
| ASTM hardness | | - | 69.0 |

The present pit has a total coal reserve of 30 million clean tonnes, and is a multi-bench, open-pit operation. The coal is not blasted, to minimize the generation of fines. It is recovered by front shovel and backhoe combination and hauled 16 kilometers to the plant with a fleet of 40-tonne capacity trucks.

Line Creek is unique in that it can simultaneously treat both metallurgical and thermal coal in separate processing facilities (refer to Figure 1.3). The thermal coal plant was commissioned in February, 1982, and the metallurgical plant in January, 1983.

Run-of-mine coal is delivered to the truck dump; one side receiving metallurgical coal and the other side thermal coal (both sides can be used for either metallurgical or thermal coal). The plus 50 mm material is scalped off and reduced to minus 50 mm in two rotary breakers. The raw coal is then conveyed to one of five, 5000-tonne capacity, silos. One silo is used for thermal coal and three for metallurgical coal (refer to Figure 1.4). One silo can be used for either thermal or metallurgical coal, although it is usually the latter.

Blending of metallurgical plant feed is achieved through the use of the four raw coal silos. Each is equipped with a variable-speed reclaim belt feeder. Conveyor scales are installed on the reclaim conveyor between the discharge of each silo, to monitor and allow control of the rate of withdrawal from each silo.

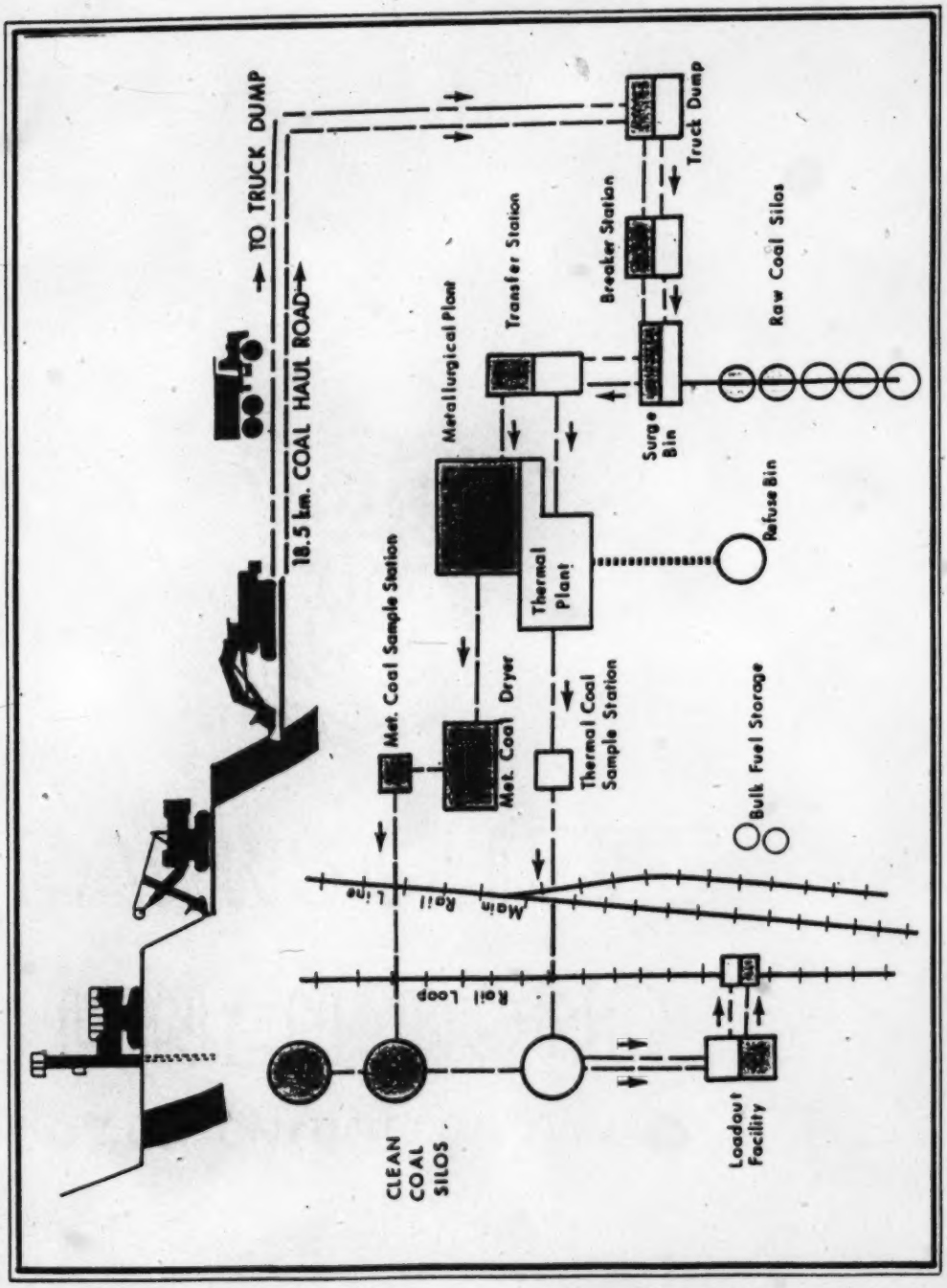



Figure 1.3 General Flowsheet of the Line Creek Mine

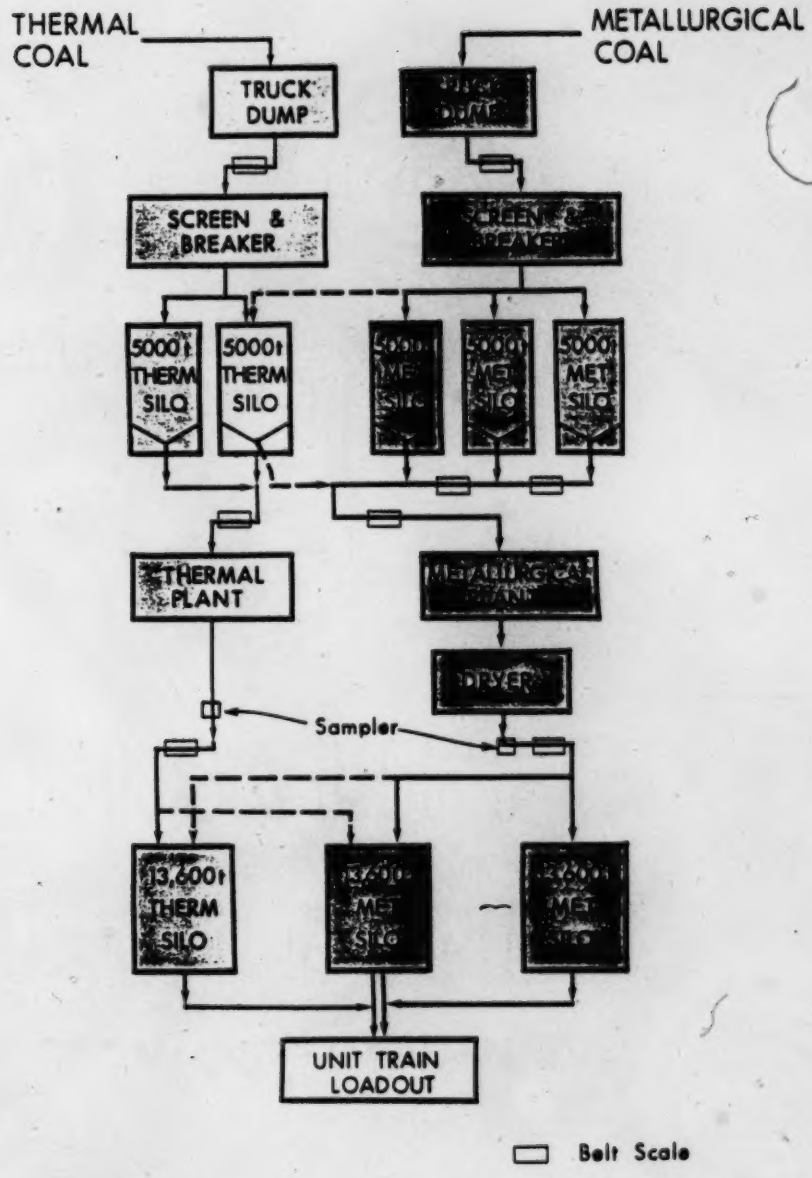



Figure 1.4 Line Creek Raw Coal and Product Blending and Storage Facilities

In the thermal coal preparation plant, coal is screened at 6 mm, with the undersize passing directly to clean coal product. The 6 X 50 mm material is washed in a heavy media vessel and the product is dewatered in a centrifuge prior to being combined with the minus 6 mm fraction. The coal is then sorted into one of three, 13600-tonne capacity, clean coal silos (refer to Figure 1.5). Since only about 40% of the feed is washed, thermal drying is not necessary to achieve the required product moisture.

The metallurgical coal preparation plant is a typical western Canadian concept with a design capacity of 380 tonnes per hour of feed (refer to Figure 1.6). The feed is screened on four deslime screens at 0.5 mm, with the 50 X 0.5 mm raw coal being washed in four, 600 mm, heavy media cyclones. Cyclone product and refuse are passed over drain and rinse screens for heavy media recovery and dewatered in basket centrifuges.

The minus 0.5 mm fraction is washed in a two-stage, water-only, cyclone circuit. There are twenty-four, 300 mm, primary and six, 300 mm, secondary cyclones. The product from the water-only cyclone circuit is screened at about 65 mesh in two stages of vibrating sieve bends. The minus 65 mesh material is fed to two banks of six, 8.5 $m^3$, froth flotation cells. The froth flotation product is combined with the sieve bend oversize and dewatered in three, 1100 X 3300 mm, screen bowl centrifuges. The coarse and fine clean coal products are conveyed by a common conveyor belt to a

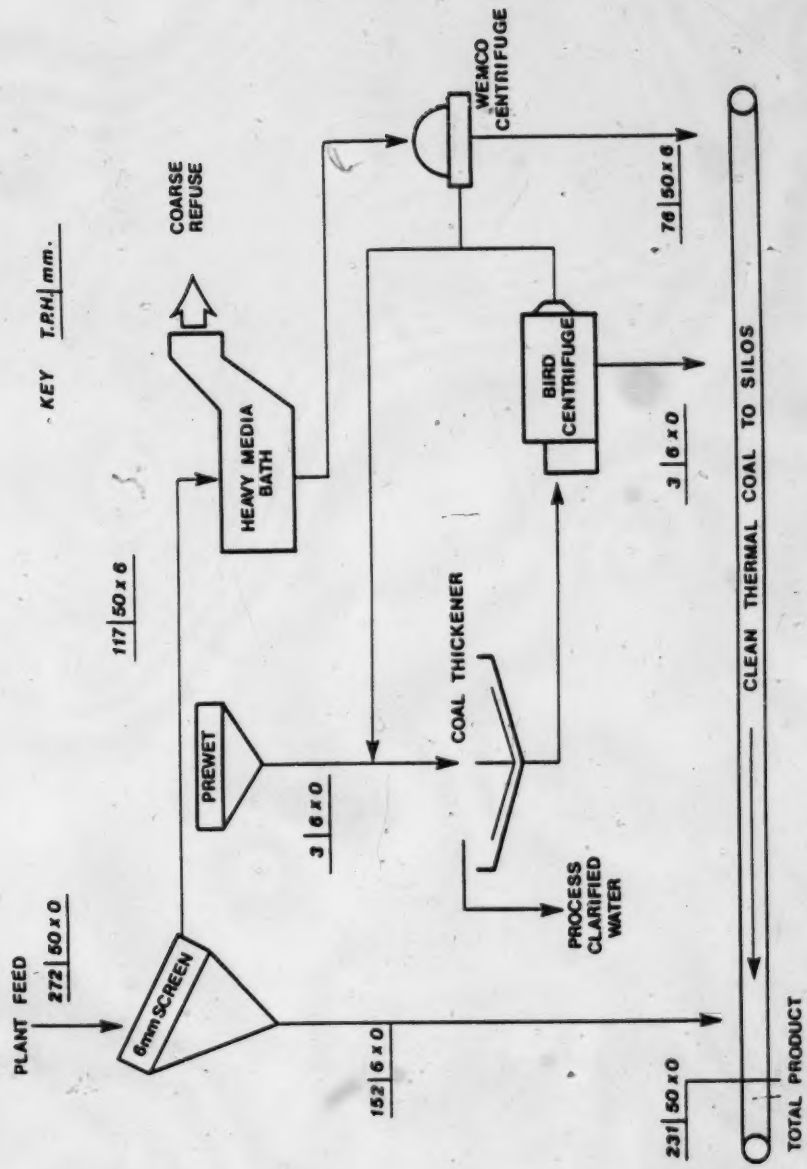



Figure 1.5 Thermal Coal Preparation Plant Flowsheet

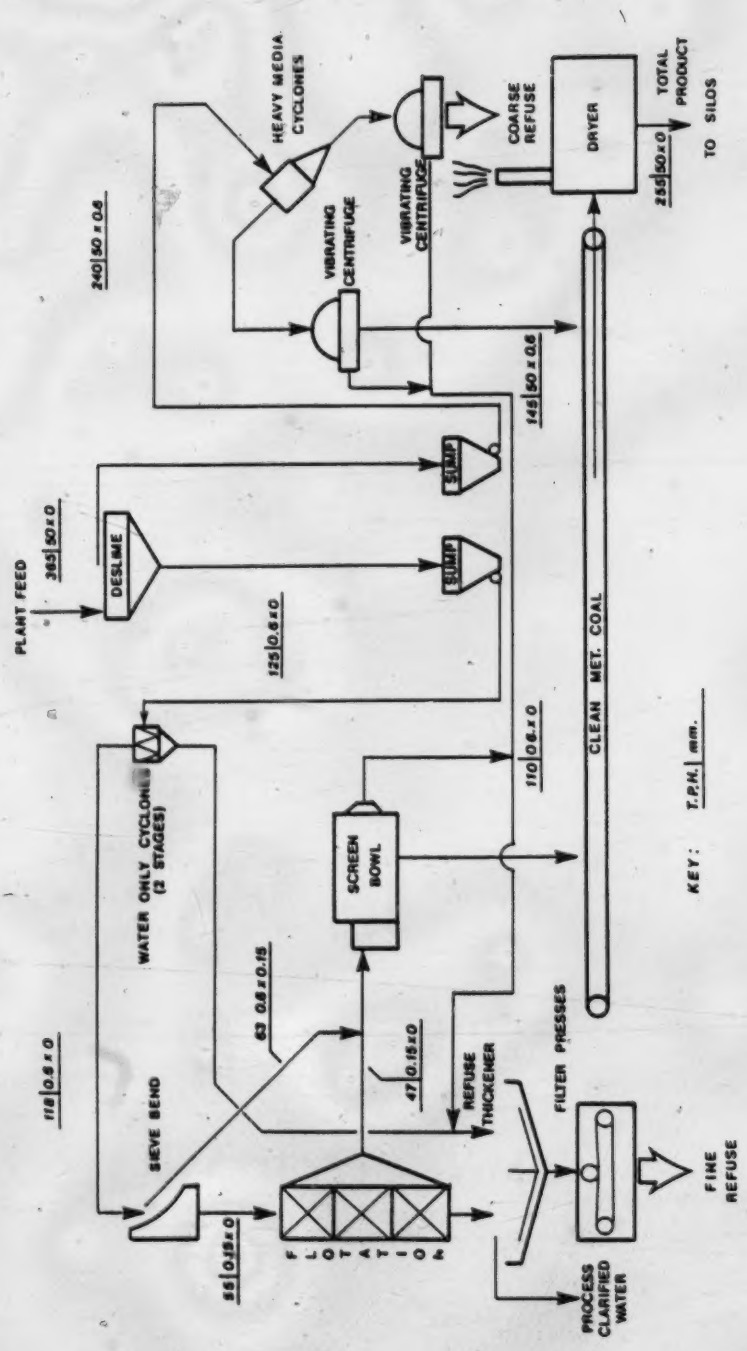



Figure 1.6 Metallurgical Coal Preparation Plant Flowsheet

natural gas-fired, fluidized bed dryer where the moisture is lowered to 7.0 - 8.0%.

A clean coal sampler takes a total stream cut of the dried product every four minutes. This material is crushed and sampled every ten seconds, by a secondary sampler, to form hourly composites for ash, F.S.I., and moisture analyses. On the basis of these results process adjustments are made to achieve target specifications. The clean coal is then stored in one of the three clean coal silos.

One important feature of the metallurgical plant is that a tailing pond is not used. Plant tailing (refuse thickener underflow) is dewatered in four belt filter presses, combined with the coarse refuse and deposited in a common refuse dump. No effluent is discharged from the plant. A MODICON control system, based on programmable logic controllers, is used for interlocks and process control purposes (e.g. dryer temperature and heavy media specific gravity).

Unit trains of 108 cars are used to transport the coal the 1100 kilometers to the port facilities at Roberts Bank, near Vancouver. Each train carries approximately 10,000 tonnes of clean coal.

## 1.4 LINE CREEK'S MOTIVATION FOR PLANT OPTIMIZATION

Line Creek's motivation for plant optimization is to produce clean coal that meets customer specifications at the lowest possible unit cost. This can be achieved by

minimizing processing costs and maximizing plant yield.

Factors that minimize processing costs include:

1) proper operating practices which minimize the cost of consumables (e.g. magnetite, flocculants, electric power, natural gas, etc.);
2) proper selection of wear items such as pipes, screens, and launders;
3) an effective equipment maintenance program.

Plant yield can be maximized by:

1) optimizing feed blends,
2) minimizing product ash fluctuations,
3) operating each circuit at the same incremental product ash.

Five major seams are mined at Line Creek. Their long-term contribution to the overall metallurgical raw coal supply is given in Table 1.2. Each seam exhibits very different washability characteristics in the heavy media cyclone circuit. Each seam also exhibits distinct yield and quality results in the water-only cyclone and flotation circuits. Consequently, plant yield and product ash levels are very sensitive to changes in feed blend.

Another variable affecting yield and clean coal ash is raw coal ash. Typical raw coal ash ranges, for each seam, are also shown in Table1.2.

Optimal blending of different seams in the feed is the most important feature of Line Creek's metallurgical plant optimization strategy and the main subject of this thesis.

Table 1.2 Relative Abundance and Ash Quality of the Five Major Coal Seams

| SEAM # | 7 | 8 | 9 | 10B | 10A |
|---|---|---|---|---|---|
| CONTRIBUTION (%) | 15 | 45 | 20 | 15 | 5 |
| RANGE OF R.C. ASH (%) | 25-45 | 18-25 | 20-27 | 20-30 | 20-30 |

On a day-to-day basis the supply of each seam can vary widely. Typically only three different seams are available for processing (usually #8 seam plus two other seams). It is, therefore very important that feed blends be optimized on a regular basis (every operating shift) for different seam availabilities.

The objectives of feed blend optimization are:

1) to maximize plant yield,
2) to minimize clean coal ash fluctuations,
3) to minimize in-plant process adjustments,
4) to maintain specified clean coal ash levels,
5) to utilize the available seams in a manner consistent with their long-term supply.

# 2. THEORY AND PRACTICE OF PLANT OPTIMIZATION

## 2.1 OBJECTIVE

The different approaches to plant optimization can be described as follows:

1) analytical techniques,
2) process simulation,
3) linear programming,
4) blending,
5) process control and automation.

The boundaries between them are not always well defined, however, for the sake of convenience each will be handled separately.

After a careful review of the literature the author presents, in some detail, the level of development of each topic and, where possible, judgement is passed on the practical application of the ideas presented.

## 2.2 ANALYTICAL TECHNIQUES

### 2.2.1 REVIEW

The distribution curve (Tromp curve, partition curve, efficiency curve, selection function, etc.) is the most useful feature in the analyses of coal washing units and circuits. When applied to washability data of a given coal, it predicts what percentage of each specific gravity fraction, making up that coal, will report to the clean coal

(C.C.) stream (some curves express this in terms of percentage reporting to the refuse stream).

The curve is derived from the washability analyses of product and refuse samples from a washing unit along with a knowledge of the clean coal yield (usually determined via the two product formula from the ash analyses of the feed, product, and refuse). It is considered to be independent of the density distribution of the feed and dependent on: the type of unit, condition of the unit, separating medium (i.e. quality of the magnetite), size composition, and feed rate. It is, therefore, independent of the feed coal, but dependent on the size range being processed. Figure 2.1 shows a distribution curve for a heavy media cyclone handling 50 mm X 0.5 mm (taken from performance evaluations carried out at the Line Creek coal preparation plant).

The specific gravity of separation $d_{50}$ (not to be confused with the specific gravity of the media) is determined from the curve and is the specific gravity at which a particle has a 50 percent chance of reporting to the product or refuse stream. The point is shown in Figure 2.1.

A number of parameters can be derived from the curve to measure the sharpness of separation of a washing unit.

**Probable Error**, Ep. A measure of the slope of the linear (not always linear) section of the curve. The steeper the curve, the lower the Ep and the sharper the separation (4,5):

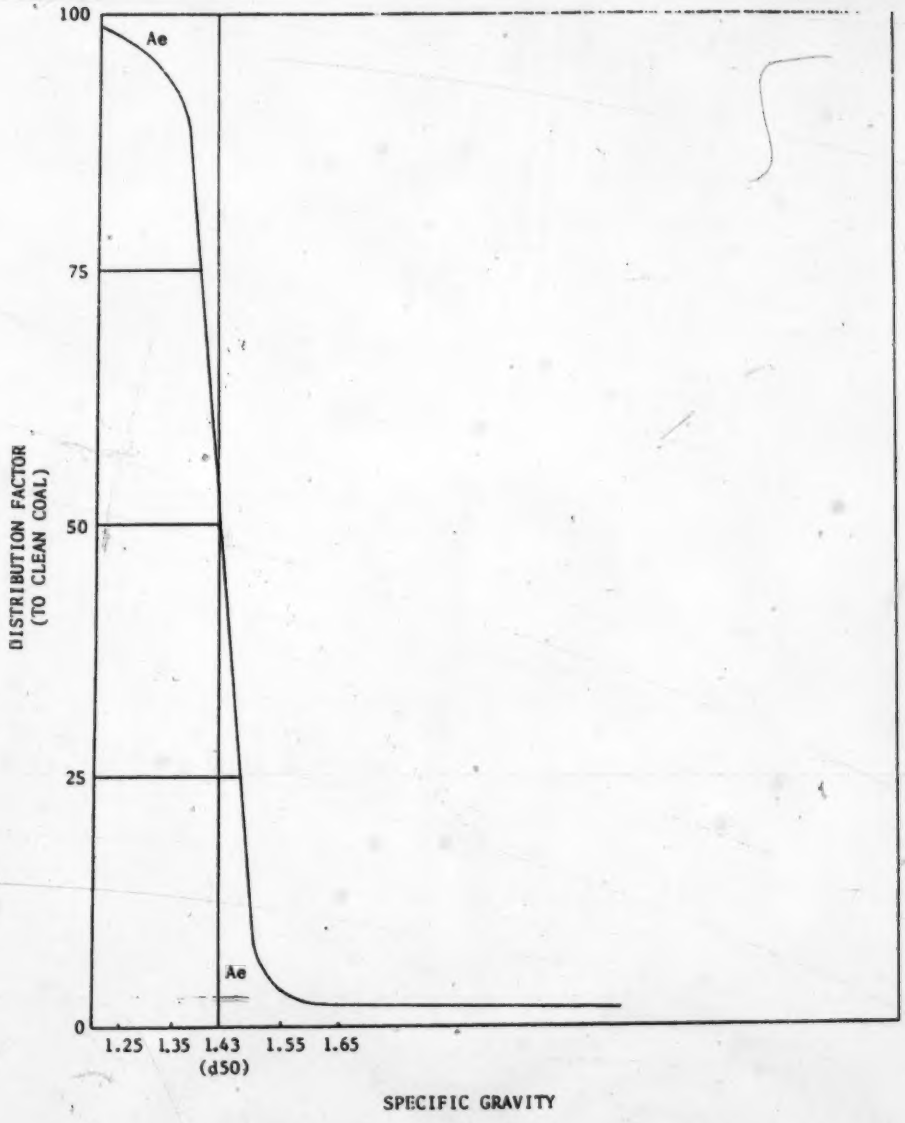



Figure 2.1 Distribution Curve for a Heavy Media Cyclone

$$Ep = \frac{d_{25} - d_{75}}{2} \qquad \ldots(2.1)$$

where: Ep = probable error
$d_{25}$ = specific gravity at the point where 25% of material reports to product
$d_{75}$ = specific gravity at the point where 75% of material reports to product

In Figure 2.1 the Ep is 0.035, a relatively sharp separation (not unusual for heavy media units).

**Imperfection**, I. Since the sharpness of separation tends to increase as the specific gravity of separation decreases (4,5), I attempts to measure the effect of the $d_{50}$ on the steepness of the curve. For heavy media units it is given by:

$$I = \frac{Ep}{d_{50}} \qquad \ldots(2.2)$$

In Figure 2.1, I is equal to 0.024.

**Error Area**, Ae. The distribution curve for a perfect separation would be a step function. The curve would run along the 100% recovery line until it reached the specific gravity of separation; at that point it would drop to the 0% recovery line for the rest of the specific gravity range. In practice, of course, this is not the case. The difference between the perfect separation curve and the real curve is the Ae, which is also a measure of sharpness of separation. The error area is shown in Figure 2.1.

It must be kept in mind that the parameters derived from the distribution curve are a measure of the sharpness of separation of a unit and as such are termed independent

criteria. They do not measure separating efficiency. The curve does not tell how much of the refuse reported to the clean coal and vice versa. Also, the effect of feed by-pass, reflected by curves that do not span the full recovery range, is not measured by these parameters and this has a significant impact on separating efficiency. The curve in Figure 2.1 exhibits this characteristic.

Separating efficiency is a measure of how much of the potentially recoverable coal present in the feed is actually recovered at a given specific gravity of separation. It is dependent on the nature of the feed as well as the separating characteristics of the equipment. Therefore, it is a dependent criteria. Parameters such as recovery efficiency (organic efficiency), ash error, and amount of misplaced material in product or refuse are used to measure separating efficiency. The author has found the concept of recovery efficiency exceptionally useful and it filled a key position in the development of the plant simulator which is covered in later chapters. It is defined as (5,6):

$$R.E. = 100\% \frac{Ya}{Yt} \qquad ...(2.3)$$

where: R.E. = recovery efficiency
Ya = actual yield obtained through a unit at the required product ash
Yt = theoretical yield at the required product ash, taken from the washability data for the coal being processed

R.E. values of 98 and 99 percent are not uncommon with some coals washed in heavy media cyclones. However, the author

has encountered values in the low seventy percent range through the same units when processing exceptionally difficult coals.

### 2.2.2 A COMMON DISTRIBUTION CURVE

Gottfried (7) presents a method of combining distribution curves at different specific gravities of separation, for a given coal washing unit and feed size range, into a single generalized curve which is independent of the specific gravity of separation. This is done by plotting the percent of feed reporting to clean coal against the reduced specific gravity X where:

$$X = \frac{\rho}{d_{50}} \qquad \ldots(2.4)$$

where: X = reduced specific gravity
$\rho$ = mean specific gravity of a specific gravity interval
$d_{50}$ = specific gravity of separation

An example of a generalized distribution curve is given in Figure 2.2 (taken from performance evaluations at the Line Creek coal preparation plant).

Gottfried also presents the idea of generalized parameters for Ep and Ae as follows:

$$Ae = d_{50}GAe \qquad \ldots(2.5)$$

$$Ep = d_{50}GEp \qquad \ldots(2.6)$$

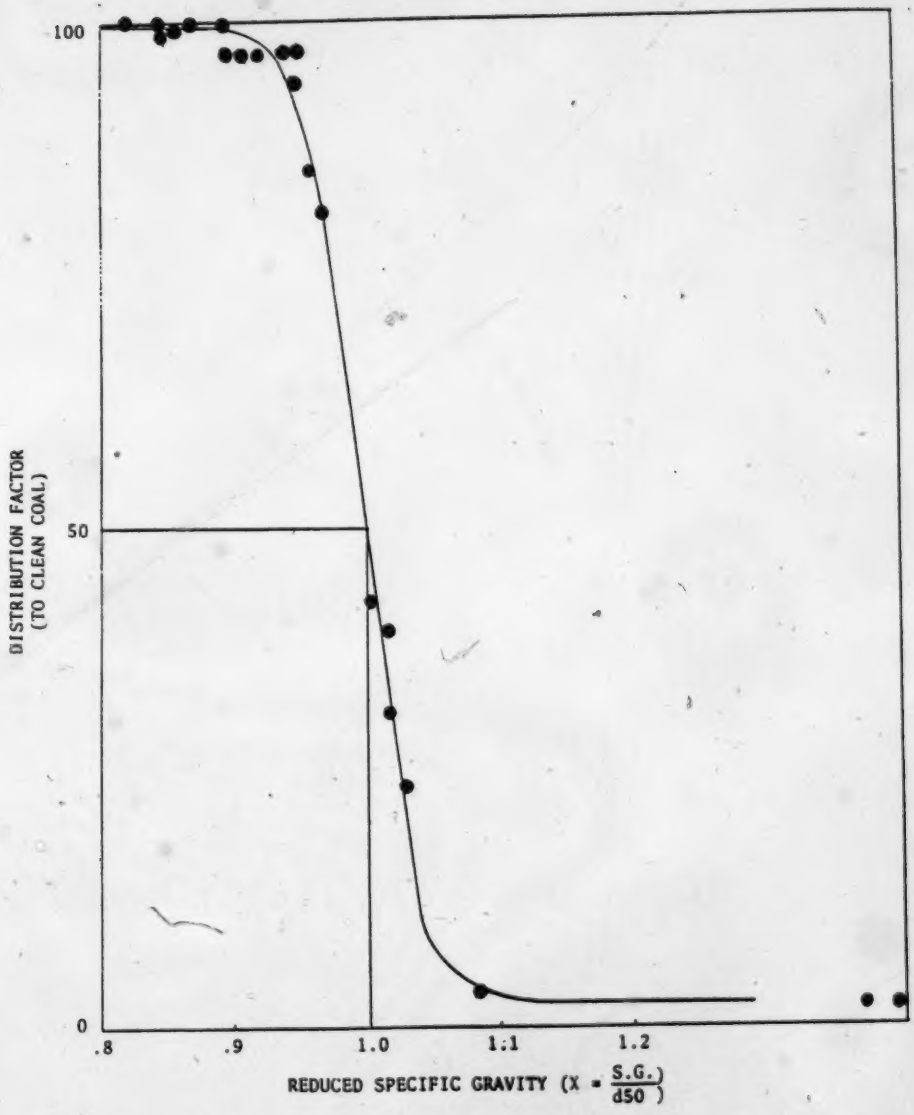



Figure 2.2 An Example of a Generalized Distribution Curve

where: GAe and GEp are the generalized forms of the parameters determined from a generalized curve
Ae and Ep are the values of the parameters at a given specific gravity of separation, $d_{50}$

Pauncz et. al. (8) utilize the concept of normalized relative density to obtain a common distribution curve that can be used for different values of specific gravity of separation and Ep. The reduced specific gravity is termed normalized relative density and is defined as:

$$\text{normalized r.d.} = \frac{(\rho - d_{50})}{Ep} \qquad \ldots(2.7)$$

This approach is probably useful if a given distribution curve is to be applied in different preparation plants where operating conditions, for a given type of washing unit, could vary widely; thus affecting the value of Ep. This is at odds with Kelly et. al. (9) who state that for gravity separators there is a limiting reduced performance curve (equivalent to Gottfried's generalized curve) for any piece of equipment that is relatively independent of operating conditions and particle characteristics (except particle size). This suggests that the value of Ep is not needed to generate a common distribution curve; since, for any given type of washing unit the value should remain relatively unchanged under different operating conditions. Maybe it depends on their definition of operating conditions; for, in the author's experience (strictly qualitative) factors such as equipment wear, magnetite quality, feed rate (or proper control of

it), feed pressure (in the case of heavy media cyclones), and proper operation of the equipment have noticeable effects on the distribution curve of a given piece of equipment. Davis et. al. (10) give a good review of how operating variables effect the distribution curve of a heavy media cyclone.

Meloy (11) presents a slightly different form of a generalized distribution curve, which he calls a characteristic R function. The reduced specific gravity Z is expressed as (for heavy media units):

$$Z = \frac{(\rho - \rho_1)}{\rho_1} \qquad \ldots(2.8)$$

where: $\rho$ = the specific gravity of the solid particles
$\rho_1$ = the specific gravity of the liquid or media (this should more correctly be called the specific gravity of separation, since for heavy media cyclones it can be significantly different from the specific gravity of the liquid)

Using Gottfied's (7) method it is possible to determine what the clean coal yield and quality of the clean coal would be at any specific gravity of separation by simply determining the value of X for each specific gravity interval of the float-sink data and determining from the curve (Figure 2.2) the percentage to clean coal which corresponds to each value of X. Table 2.1 shows a sample calculation from actual operating data, using reconstituted feed at a $d_{50}$ of 1.50.

This approach has been used to define the sharpness of separation of the heavy media cyclone circuit at the Line

Table 2.1 Yield and Ash Calculations From a Generalized Curve

| MEAN S.G. | % WT OF FEED | %A | $\frac{S.G.}{d_{50}}$ (X) | DISTRIBUTION FACTOR (D.F.) | D.F.X %WT | %A X $\frac{D.F. \times \%WT}{YIELD}$ |
|---|---|---|---|---|---|---|
| 1.25 | 25.62 | 3.37 | 0.833 | 0.994 | 25.47 | 1.17 |
| 1.35 | 36.19 | 8.88 | 0.900 | 0.990 | 35.83 | 4.34 |
| 1.45 | 13.27 | 16.98 | 0.967 | 0.819 | 10.87 | 2.52 |
| 1.55 | 5.02 | 26.11 | 1.033 | 0.175 | 0.88 | 0.31 |
| 2.20 | 19.90 | 64.15 | 1.467 | 0.015 | 0.30 | 0.26 |
| | | | | | % YIELD = 73.35 | % ASH = 8.60 |

Creek plant with very good results. It was incorporated in the development of the plant simulator, allowing the characterization of the heavy media cyclone circuit with a single generalized curve.

### 2.2.3 GENERAL POINTS ABOUT DISTRIBUTION CURVES

When coal is washed a degree of particle degradation and liberation takes place. For this reason, when using a given distribution curve, the washability results from reconstituted feed should be used if possible. This will provide the most accurate performance predictions.

The plotting of a distribution curve can be quite subjective and depends to a large degree on experience. The location of $d_{50}$ can be difficult to determine if the number of data points is insufficient in the centre section of the curve. Kapur (12) presents a method of linear interpolation which allows estimation of $d_{50}$ from the two nearest points bracketing this region. It is given as:

$$d_{50} = d' + \left[\frac{d'' - d'}{t' - t''}\right](t' - 50) \qquad \ldots(2.9)$$

where: d' and t' are the specific gravity and corresponding distribution number, respectively, of the nearest point over $d_{50}$
d" and t" are the specific gravity and corresponding distribution number, respectively, of the nearest point below $d_{50}$

The method is strictly numerical with no interpretation required. However, it could lead to serious error if the nearest point above or below is located on the highly

nonlinear portion of the curve. Also, data points do not always lie on the plotted curve and some interpretation or *smoothing*, based on previous experience, is often required. It must, therefore, be concluded that determination of $d_{50}$ from the actual distribution curve is more reliable, if to some degree subjective.

Absil et. al. (13) have developed an empirical relation, arrived at from extensive operating data, to predict the Ep of a given unit if the $d_{50}$ is known or at least anticipated. The relation is:

$$Ep = K1 + K2d_{50} + K3d_{50}^2 \qquad ...(2.10)$$

where: K1, K2, and K3 are constants given in Table 2.2.

The approach could be useful in the design stage in the absence of distribution curves or where a general idea of Ep is required, without extensive testing. The author has found that results calculated from the relation agree with those obtained from distribution curves, for heavy media baths and cyclones.

Based on the literature the following general statements can be made:

1) sharpness of separation increases (Ep decreases) as $d_{50}$ decreases,
2) $d_{50}$ increases as the particle size decreases,
3) sharpness of separation decreases as particle size decreases,
4) the narrower the particle size range covered by a given

Table 2.2 Empirical Constants for Determination of Ep

| | $K_1$ | $K_2$ | $K_3$ |
|---|---|---|---|
| Cyclone washer | -0.01 | 0.027 | 0 |
| Heavy media bath | -0.05 | 0.047 | 0 |
| Jig washer (shale/coal + middling) | 0 | -0.099 | 0.099 |
| Jig washer (coal/middling) | 0 | -0.078 | 0.078 |

distribution curve the more reliable the results.

The mathematical representation of distribution curves, which is of great importance in process simulation, will be covered in next section 2.3.2.

## 2.2.4 CIRCUIT ANALYSES

### 2.2.4.1 Optimal Arrangement of Washers

There are three types of arrangements that can be considered for coal preparation (only the first is widely used):

1) Different types of washers in parallel, each treating a different size fraction (refer to Figure 1.1) - each washer being best suited for that size fraction. How this is accomplished in an optimal manner will be covered later in this section.

2) Two or more stages of the same equipment in series at different cut points (refer to Figure 2.3), typically called a rougher scavenger circuit. Kelly et. al. (9) warn that under no circumstances should the scavenger product be recycled without regrinding, since the middling particles thus recovered would either contaminate the product or be lost to refuse. This is true only for true middling particles, however, misplaced clean coal can be recycled without regrinding. The water-only cyclone circuit in Figure 1.1 is an example.

A variation of this concept is the use of a

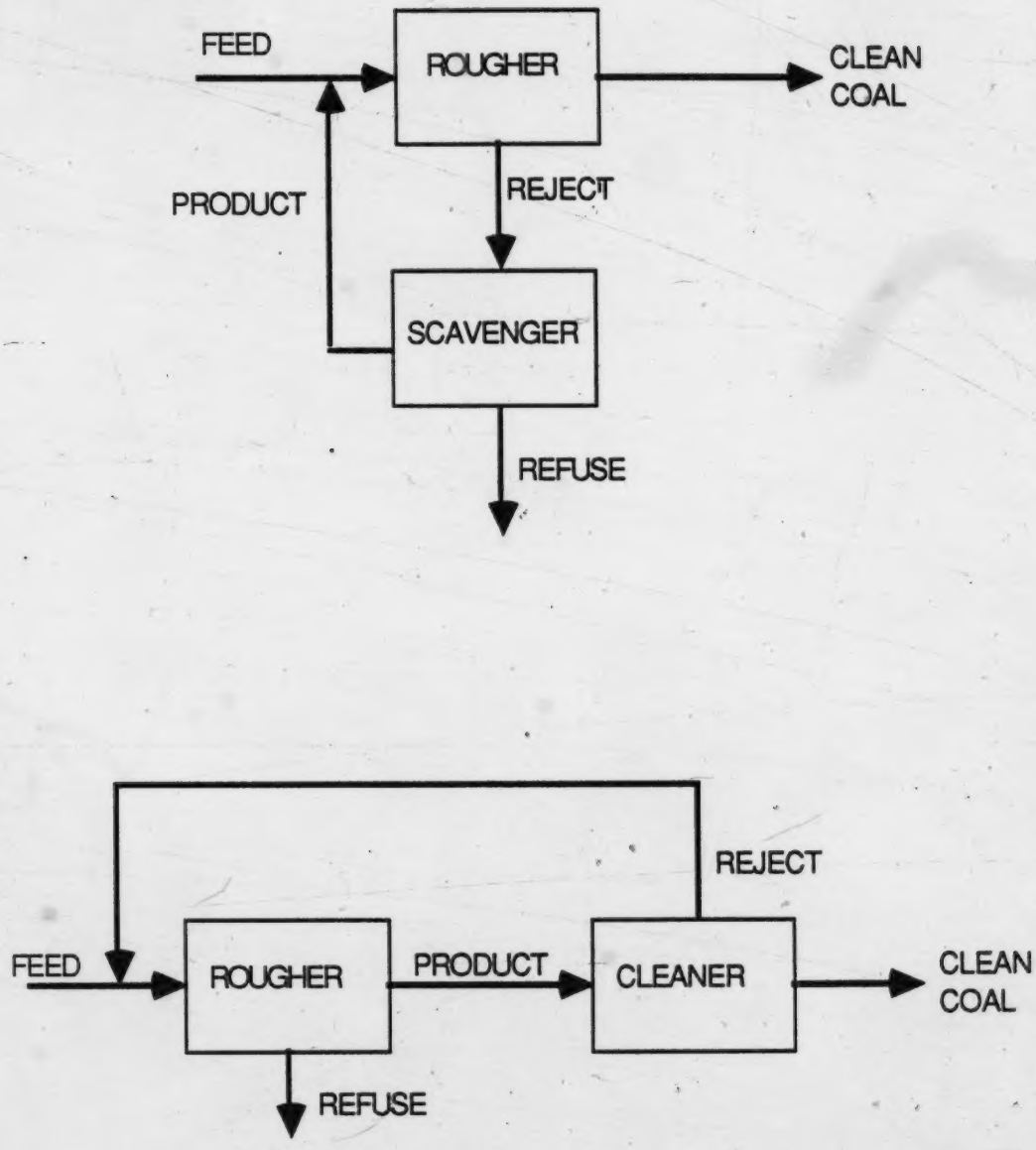



Figure 2.3 A Rougher-Scavenger and a Rougher-Cleaner Circuit

different unit to recover coal from the primary unit reject (tailing). An example would be the use of spirals to recover coal from flotation tailing (presently being evaluated at Line Creek).

3) Two or more stages of the same equipment in series with the same separator settings, typically called the rougher cleaner circuit (refer to Figure 2.3). Although not used for coal, it may be applicable with less efficient separators where more than one cleaning step may be beneficial (i.e. treatment of fine coals). This will be reviewed later.

Meloy (11) proposes that the rougher cleaner scavenger circuit shown in Figure 2.4 is an optimal arrangement. Although this circuit is not used for coal, the mathematical relations presented have potential. Salama and Mikhail (14) give some variations of Meloy's principles.

The R function represents distribution factor values at different values of Z (reduced specific gravity, equation 2.8). Meloy demonstrates that the slope at $d_{50}$ (sharpness of separation) increases as the number (n) of washers in the cleaner and scavenger legs increases. This is illustrated by the following equation:

$$Rc = \frac{R^n}{R^n + \hat{R}^n} \qquad \ldots(2.11)$$

where: Rc = overall circuit distribution values
$\hat{R} = 1 - R$
(this assumes identical units with equal R

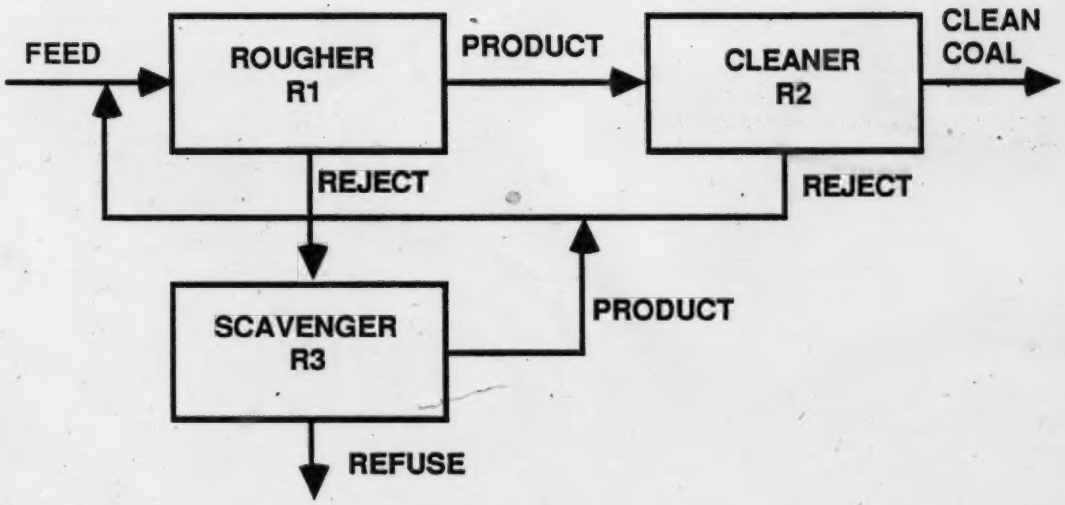



Figure 2.4 A Rougher - Cleaner - Scavenger Circuit

functions)
n = number of units in the cleaner and scavenger legs

It can be seen that for values of specific gravity below $d_{50}$, Rc tends to 100 percent and for values of specific gravity above $d_{50}$, Rc tends to 0, as n increases.

Feed by-pass, directly to clean coal or refuse, is common in heavy media cyclones. This is illustrated in Figure 2.1 where the distribution curve does not span the 0% to 100% range of distribution values. Meloy gives the following simple model for by-pass:

$$Rc = \left[1 - \overline{\overline{BP}}(1 - \overline{\overline{BWR}})\right] \qquad ...(2.12)$$

where: $\overline{\overline{BP}}$ = by-pass function to product
BW = by-pass function to reject

Rearranging this equation gives the separating characteristic of the unit, if by-passing could be eliminated:

$$R = \frac{Rc - 1 + \overline{\overline{BP}}}{\overline{\overline{(BP)}}\,\overline{\overline{(BW)}}} \qquad ...(2.13)$$

2.2.4.2 Theoretical Maximum Yield Principles

The literature makes frequent references (6,15,16, etc.) to the incremental ash principle for yield maximization. Simply stated: yield is maximized if each feed stream (in parallel) is washed to the same level of incremental ash. It has been demonstrated (6,15) that for washers with reasonably sharp distribution curves

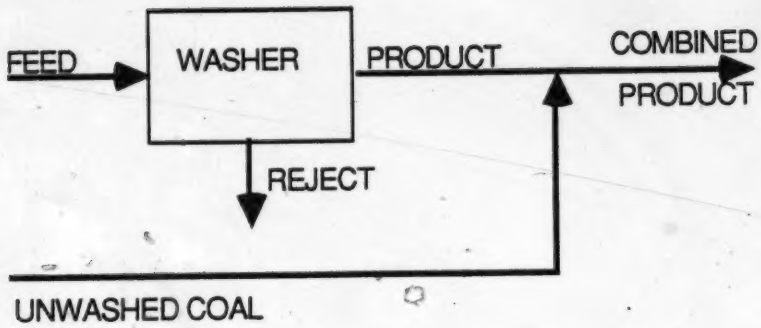
this principle holds true in practice.

Cierpisz et. al. (15) present other maximum yield principles:

1) For a single washer with by-pass (refer to Figure 2.5) maximum clean coal production will be obtained when the incremental ash in the washed coal is equal to the cumulative ash in the unwashed stream.
2) For a single washer with by-pass and fixed feed rate (refer to Figure 2.5) maximum yield, at a given clean coal ash, will be obtained when all the feed is washed (no by-pass).
3) For theoretically perfect washers, there is no benefit in passing the product or refuse from one washer through another washer. In practice this is not the case. Real washers do not achieve a perfect cut in one pass, therefore, each successive passage provides a new opportunity to recover product material, in the case of retreatment of reject; or remove reject, in the case of retreatment of clean coal (9).

2.2.4.3 Summary

It must be kept in mind that some coals have very favourable washing characteristics with a minimum of near gravity material and that a high recovery efficiency may be possible (5) with a less efficient and less expensive washer. Also, for a given coal or group of coals, a compromise must always be reached between



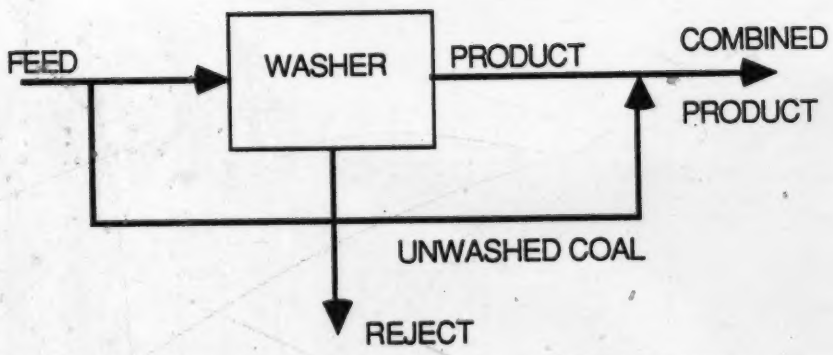




Figure 2.5 Bypass Configurations for a Single Washer

sharpness of separation and equipment capital and operating costs. Maximum return on investment, not maximum yield, is the controlling factor.

## 2.3 PROCESS SIMULATION

### 2.3.1 REVIEW

#### 2.3.1.1 Utility of Models

Process simulation through computer modelling is becoming increasingly common in coal preparation. Models show great utility in the following areas:

- optimizing flowsheet design,
- estimating capital and operating costs,
- gaining process knowledge,
- optimizing the process (off-line),
- assessing alternate control strategies,
- comparing with actual results to detect problems or losses,
- predicting the effects of different feed blends.

Different models (according to the literature) capable of doing some of the above tasks will be covered later in this section.

#### 2.3.1.2 Types of Models

The models typically used to simulate a coal preparation plant are of the conceptual type. They are

an abstract representation of the process usually in the form of mathematical relationships between independent process variables and important dependent responses, such as yield. They can be represented by the following general equation (17):

$$Y_i = f(x_{1i}, x_{2i}, \ldots, x_{ni}; a_1, \ldots, a_n) + e_i \quad \ldots(2.14)$$

where: $Y_i$ - dependent response at the i th setting of independent variables $x_{1i}, x_{2i}, \ldots, x_{ni}$
$a_1, a_2, \ldots, a_k$ - constants
$e_i$ = error term or residual

If the equation is known from basic physical and chemical principles the model is mechanistic or theoretical. If it is obtained from direct experimentation on the process unit, the model is empirical. Empirical models are usually easier to derive.

Models can be further subdivided into stochastic or non-stochastic (deterministic). Stochastic models take into account the random variations in a process. Non-stochastic models do not consider random variations.

These definitions are by no means universal. Walters and Ramani (18), for example, offer a somewhat different view.

2.3.1.3 Fitting of Empirical Models

Linear response models can be efficiently fitted by taking advantage of the property of orthogonality in the pre-selection of variable settings. This permits direct

calculation of the best coefficients in the equation (17). If a model is too complex for this approach (experimental design cannot be used) standard regression techniques can be utilized, provided the response is linear.

The fitting of nonlinear models is more difficult and usually requires the use of a computer. The following mathematical techniques are available to fit non-linear models:

- transformation to a linear model
- derivative methods that utilize information about the objective function gradient.
- derivative-free methods that utilize pattern multivariable search strategies.

Mular (17) presents a brief description of each.

Once a model has been determined it must be tested for adequacy of fit (that it truly represents the process). This is done by:

- examining the residuals,
- determining the significance of terms (dropping those that are not significant),
- testing for lack of fit (test for curvature in the case of linear models),
- comparing predicted to actual process results.

Only after these steps are satisfied is the model considered valid.

2.3.1.4 Model Based Optimization

In the case of process models, optimization means selection of values (settings) of the independent variables that will give an optimum response (yield, profit, etc.). This is illustrated graphically by the response surface given in Figure 2.6. If $X_1$ and $X_2$ represent reagent settings in a bank of flotation cells [$X_1$ = kerosene addition rate and $X_2$ = MIBC (frother) addition rate]. The response surface could represent the constant yield contour lines. The point of maximum yield identifies the optimum settings of the control parameters, if the product ash requirement is satisfied.

If a valid model is available then off-line optimization is possible to determine the best settings of the control parameters. This can be done by using the derivative or derivative-free methods already mentioned. Abara and Gottfried (19), for example, utilize the Hooke-Jeeves method for their optimization algorithm.

If a model of the process does not exist, on-line optimization (requiring direct adjustments to the process) is possible through one of the following techniques: grid search, one variable at a time, steepest ascent, EVOP and SSDEVOP. Mular's paper (17) contains a summary of these techniques.

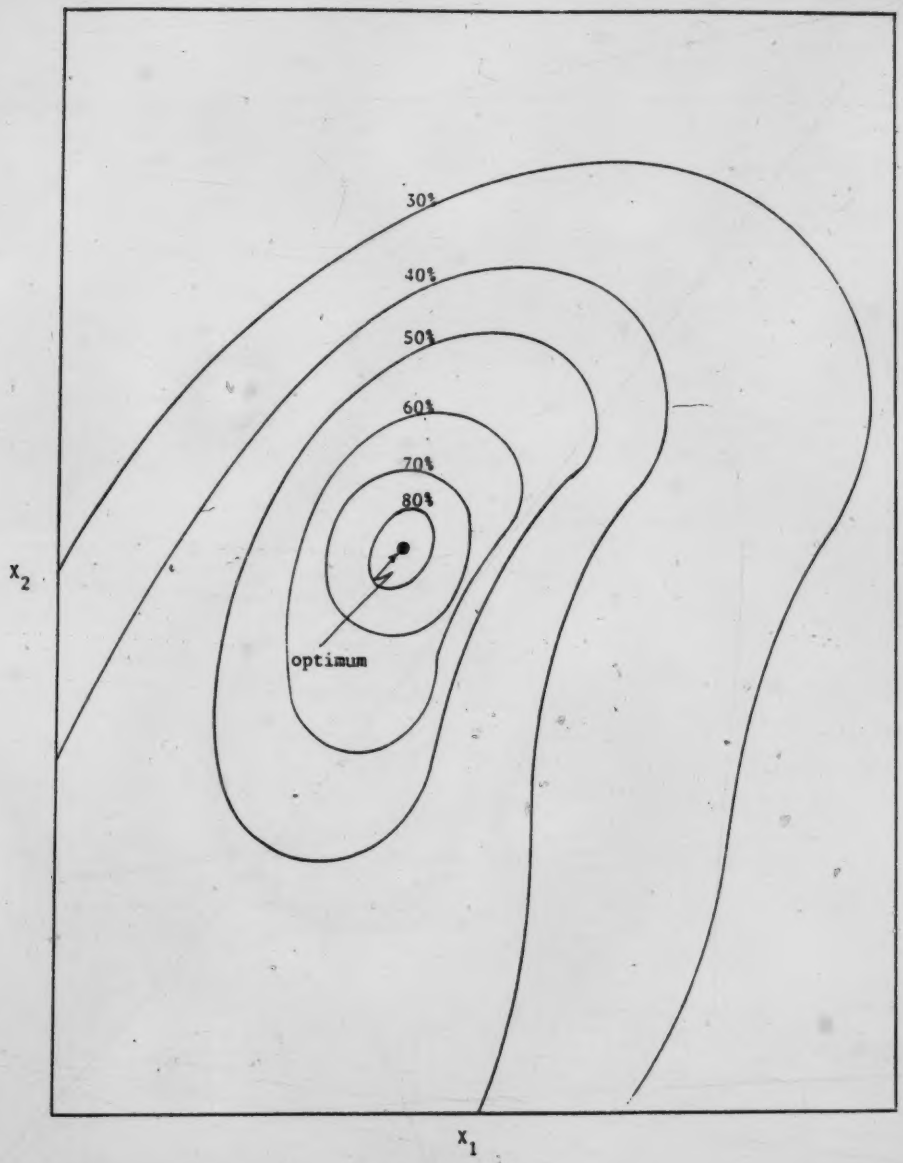



Figure 2.6 A Yield Response Surface

## 2.3.2 MATHEMATICAL REPRESENTATION OF DISTRIBUTION CURVES

It is often convenient to express the distribution curve as a mathematical equation. The most important application of this is in the formulation of computer models for coal preparation. With the increased use of models for plant optimization, the search is on for the equation which best represents the separating characteristics of a given coal washing unit. A few of these are presented here.

Gottfried (7) suggests that the Weibull function, an exponential type distribution, can be used to mathematically represent a generalized distribution curve. For heavy media separators, whose distribution curve may not vary from 0 to 100 percent, it is expressed as:

$$f(x) = 100\left[f_0 + C\exp\left\{-\frac{(x - x_0)^a}{b}\right\}\right] \quad \ldots(2.15)$$

where: f(x) = distribution factor (percent feed to product)
a, b, C, and $f_0$ = positive and independent constants
X = reduced specific gravity
and

$$x_0 = 1 - \left[b\ln\left[\frac{C}{0.5 - f_0}\right]\right]^{\frac{1}{a}}$$

Since $f_0 + C \leq 1$, the function varies from a maximum value of $100 (f_0 + C)$ to a minimum value of $100 f_0$.

The independent constants (a, b, c, and $f_0$ must be determined for a given set of distribution data. This can be done by a nonlinear regression technique. Gottfried (7) has

tabulated values of these constants for different units and feed size fractions.

By mathematical manipulation and substitution, he derives an expression for the generalized Ep (equation 2.6) as a function of the independent constants:

$$GEp = 0.5\left[\left\{b\ln\left(\frac{C}{0.25-f_0}\right)\right\}^{1/a} - \left\{b\ln\left(\frac{C}{0.75-f_0}\right)\right\}^{1/a}\right] \quad ...(2.16)$$

He claims to obtain results similar to those determined from distribution data.

Although the Weibull function represents the tabular data reasonably well, two main problems are mentioned.

1) Many curves tend to break too sharply in the highly nonlinear regions, i.e. at the *shoulders* of the curve.
2) For those sets of data that span the complete range of values from 0 to 100 percent, the fitted curve often falls short of spanning this range.

In spite of these limitations the function has been found useful in computer modelling. Wizzard et. al. (20) make use of the Weibull function in their computer program to calculate the performance characteristics of coal washing units. Peng (21) suggests the use of the Weibull function to represent units operating under disturbed or poor conditions (perhaps making use of problem 2, mentioned above).

Trawinski (22) presents a multitude of equations to fit almost any imaginable shape of normalized (generalized) curve for wet particle classification. It is left up to the reader to examine the full range of equations, since only the main ones are presented here.

$$Y = \frac{e^{\alpha x} - 1}{e^{\alpha x} + e^{\alpha} - 2} \qquad \ldots(2.17)$$

$$Y = 1 - 0.5^{x^{\alpha}} \qquad \ldots(2.18)$$

$$Y = \frac{1}{2^{(1/x)^{\alpha}}} \qquad \ldots(2.19)$$

where: $Y$ = distribution factor ($0 \leq Y \leq 1$) reporting to the coarse stream
$x$ = reduced size = $d_i/d_{50}$
$d_i$ = particle size
$d_{50}$ = cut size (equiprobable distribution size analogous to the specific gravity of separation)
$\alpha$ = a parameter measuring the sharpness of separation that must often be determined empirically from masses of operating data and some educated guesswork

Peng (21) introduces the following equation, based on the normal probability density function, for properly operated equipment such as heavy media baths and cyclones:

$$P = \frac{1}{\sqrt{2\pi}} \int_0^1 e^{-0.5\tau^2} d\tau \qquad \ldots(2.20)$$

where

$$\tau = \frac{(\rho - d_{50})}{\sigma} \qquad \ldots(2.21)$$

where: $\rho$ = specific gravity
$\sigma$ = standard deviation

A different approach suggested by Erasmus (23) involves the linearization of the distribution curve. The linearized curve is expressed as:

$$\tan^{-1}(K(\rho - C)) = t_2 - \frac{t_2 - t_1}{100} P \qquad \ldots(2.22)$$

where: P = distribution factor in percent
$\rho$ = corresponding specific gravity
K, C, $t_1$, and $t_2$ - "quasi-constants" dependent on $d_{50}$ and must be determined by linear regression techniques

A curve fitting approach is given by Walters and Ramani (24) where linearity of the distribution curve is assumed between $d_{25}$ and $d_{75}$. In the nonlinear sections (shoulders), interpolation of distribution factors between known points is accomplished by a computer program using a "one-dimensional quasi-cubic hermite interpolation function".

### 2.3.3 MATHEMATICAL REPRESENTATION OF OTHER PROCESSES

#### 2.3.3.1 Water-Only Cyclones

Turak (25) presents an empirical model for automedium cyclones based on three separation stages:

1) Primary classification in the upper cylindrical section where fine material is sent to overflow. Coarser material and material carried by the by-pass

stream are carried downward along the cyclone wall to the stratified bed.

2) The material is then stratified in the non-stationary bed in the conical section. Coarser and heavier material leave via the apex and lighter material is lifted from the bed to a secondary classification.

3) This takes place in the upward flow of the vortex. Light material is discharged to overflow and coarse and heavy material is returned to the bed.

The model form is:

$$p_{ij} = (r_{ij} + (1-r_{ij})c_{ij}) \frac{1 - a_{ij}}{1 - a_{ij}b_{ij}} \quad ...(2.23)$$

where: $p_{ij}$ = fraction of i th size class and j th specific gravity class that reports to the underflow (reject)

$r_{ij}$ = by-pass function for i th size class and j th specific gravity class which is short-circuited to the bed

$c_{ij}$ = partition function for primary classification for i th size class and j th specific gravity class

$a_{ij}$ = partition function for autogenous heavy media separation in the bed section for ith size class and jth specific gravity class

$b_{ij}$ = partition function for secondary classification for the i th size class and j th specific gravity class

The separation functions are determined from seven parameters derived from experimental and plant data. Although the model provides a good fit with observed results, the large number of parameters make it cumbersome to use. Further work is suggested to reduce

the model to a simpler form.

2.3.3.2 Flotation

A fully adequate flotation model, capable of describing an actual plant environment, has not been developed. Some authors (26) use an approximation of yield and ash depending on the properties of the feed, while others (27) simply specify yield and quality values in their program. None-the-less, Peng (21) makes a particularly valiant effort with the following semi-empirical model, which she employs in her simulation program of coal cleaning circuits:

$$\frac{r}{R} = 1 - \sum_{u=1}^{P} \frac{P_{R,u}}{K_u t}\left[1 - e^{-K_u t}\right] \qquad ...(2.24)$$

for P discrete size distributions, or

$$\frac{r}{R} = 1 - \frac{1}{Kt}\left[1 - e^{-Kt}\right] \qquad ...(2.25)$$

for monodisperse feed,
where: r = fraction of coal recovered at time t
$P_{R,u_u}$ = mass fraction of coal in particle in the u'th size range
$K_u$ = rate constant of coal particle in the u'th size range
R = overall equilibrium yield

The best values of parameters R and K in the model for a given data set is determined by minimizing the square deviation between measured and calculated yields for the sum of all time points (q):

$$\text{minimize} \left\{ \sum_{v=1}^{q} \left[ r_{v(\text{measured})} - r_{v(\text{predicted})} \right]^2 \right\} \qquad ...(2.26)$$

She also makes reference to the following model for well mixed continuous flotation cells in series:

$$Rc = 1 - \frac{1}{\left[1 + K(k,x,g)\theta\right]^N} \qquad ...(2.27)$$

where: Rc = distribution factor to product
K(k,x,g) = rate constant (may be determined from laboratory or plant tests)
k = quantifies surface characteristics
x = particle size
g = quantifies mineralogical composition
$\theta$ = average residence time of pulp for each cell
N = number of cells in series

Unfortunately, the accuracy of these models is not given.

2.3.3.3 Screening

The following equation (28), based on the probability of passage, for the distribution curve of a screen has been presented:

$$P = \left\{ 1 - \left[\frac{a - d}{a + w}\right]^m \right\}^n \qquad ...(2.28)$$

where: P = distribution factor to oversize stream
d = mean particle size of size range
a = screen opening
w = width of wire
m = 1 for rectangular openings , 2 for square openings
n = number of times a particle falls on the screen (n is the same for all sizes and is a function of the screening action)

For wet screening, down to 0.5 mm, the following simple model has been proposed (27):

$$P = e^{-A(1 - \frac{d}{a})} \quad \ldots(2.29)$$

where: A = constant (a value of 5 is suggested)

It is claimed that this model represents the distribution curve reasonably well after some trial and error to find the best value of A.

2.3.3.4 Crushing

Crushing tends to be difficult to model since two functions must be considered: the selection function $S_i(B)$ which is the fraction of feed particles in the i th size range that will be crushed at a given crusher setting, B; and a breakage function $B_{ik}(B)$ which is the fraction of crushed particles originally in the i th size range that reaches the k th size range. It is assumed that the breakage of a particle creates fragments which are unchanged in specific gravity analyses and that these fragments are dependent on initial particle size but independent of specific gravity. These assumptions are questionable when dealing with coal (one simply has to look at the reject pile from a rotary breaker).

Gottfried and Abara (19, 26) model a rotary breaker by a combination of crushing and screening events.

2.3.3.5 Filtration

Osborne (29) presents the following general equation (suggested by an earlier author) for

filtration:

$$\frac{E}{A} = \frac{\Delta P}{\frac{\mu \rho W V}{A} + R} \qquad \ldots(2.30)$$

where: E = feed slurry rate
A = filter area
$\Delta P$ = filtration pressure drop
$\mu$ = filtrate viscosity
$\rho$ = cake specific resistance
W = solids mass per unit volume of filtrate
R = filter media resistance
V = filtrate volume

The values of some of these parameters are difficult to determine ($\mu$, $\rho$, W) and they are not constant over time. Osborne also gives several equations for specific types of filters.

Peng (30) uses the following general equation for: plate and frame filters, rotary vacuum filters, leaf filters, and centrifuges.

$$\theta_f = nK1V^2 + K2V \qquad \ldots(2.31)$$

where: $\theta_f$ = filtration time
$V^1$ = volume of filtrate
n = 1 for constant pressure filtration, and 2 for constant rate filtration
K1 and K2 = constants specific to the type of filter used (these are described by equations given in her paper)

Tierney et. al. (31) present a series of equations that can be used to predict the performance of vacuum filters and centrifuges and are the basis for a dewatering module which was added to the coal preparation simulator developed at the University of Pittsburg for the U. S. Department of Energy (will be

reviewed later).

2.3.3.6 Thickening

Wilhelm and Naide (32) present an interesting discussion of continuous thickening theory which may be applicable to process modelling (no evidence of this was found). They give the following empirical equation which relates thickener loading rate to the desired underflow concentration:

$$G2 = ab\left[\frac{b-1}{b} C_u\right]^{1-b} \qquad ...(2.32)$$

where: G2 = limiting solids flux (weight of solids/time X unit area)
a,b = constants determined from batch settling data
$C_u$ = underflow concentration

## 2.3.4 COMPUTER SIMULATORS FOR COAL PREPARATION

2.3.4.1 Description

A variety of simulators are mentioned in the literature with a wide range of capabilities. These could be roughly described as process simulators or economic simulators (some are both). Process simulators deal mainly with the calculation of material balances; whereas, economic simulators are concerned with the best estimation of capital and operating costs, and return on investment. Both types can work together and this is often the case when optimizing flowsheet design.

In the following review, coal preparation simulators are presented under one of these classifications. As far as possible they are listed in order of development.

2.3.4.2 Process Simulators

A rather primitive computer simulator was presented by Weyher (33) in 1971 on behalf of the Homer Research Laboratories of Bethlehem Steel Corp. It was able to model gravity separation units using feed washability analyses and distribution curves. Modelling of crushing and other processes was not possible. It was, however, able to calculate fixed and variable costs for alternate flowsheet designs. It was used for process performance evaluations and flowsheet design.

A more flexible simulator, developed for the U.S. Department of Energy at the University of Pittsburg, was presented by Gottfried (34). It was capable of modelling washers, crushers, and screens. An approximate method, based on the properties of the feed, was used to represent flotation. Gottfried and Abara (19,26) later applied the Hooke-Jeeves method of optimization with the simulator to optimize plant yield within ash and sulfur constraints. Predicted results did not correspond well with actual plant results, however it was useful for indicating optimal operating strategies. Development of the simulator continued in succeeding years and eventually classifying, dewatering, thickening, and

drying modules were added.

Goodman et. al. (35) upgraded Gottfried's original simulator by improving the FORTRAN and the documentation. The ability to determine capital costs was also added.

The simulator was later (36) transferred to a microcomputer (APPLE II) to obviate the need for a main frame. Although slower and more cumbersome (due to the need to change disks) it should allow more widespread use.

An offshoot of the simulator is described by Wizzard et. al. (20). The program uses the specific gravity analyses of the clean coal and refuse as input, and generates dependent and independent performance criteria for coal washing devices. Distribution curves are internally represented by Weibull functions. Results are typically in agreement with hand-calculated values.

Firth et. al. (27) have developed a modification of the U.S. Bureau of Mines' simulator, in Australia. The model is termed COSCOP and is claimed to be superior in the following ways:

- allows blending of different feeds,
- contains an improved screening model,
- contains an improved flotation model (this is very questionable since flotation yield and clean coal ash must be input to the COSCOP model),

- is easier to manipulate.

The Australian Coal Industry Research Laboratories Ltd. have developed a simulator (8) for use in the performance prediction of coal preparation plants. It is made up of the following programs:

- 4 MATT, which allows washability data, expressed in different specific gravity intervals, to be reformatted to be compatible with the simulator,
- 4 COMP, which allows the user to select the proportion that each size fraction will contribute to the overall feed composite,
- 4 CAST, which contains distribution data for specific-gravity-based washing units such as heavy media cyclones, jigs, water-only cyclones, etc.

Superwash, is another Australian simulator developed by the Davy McKee Pacific Pty Ltd. (37). It carries out automatic expansion of washability data, plots washability curves for single and composite coals, and determines the optimum setting of control parameters to achieve maximum yield at specified clean coal ash levels. Only specific-gravity-based washing units are modelled.

The Spoc Manual (38) published in 1985 made some further improvements to Gottfried's simulator (better documentation and improvements in the FORTRAN). It can

be used with an optimization strategy to optimize process variables within given quality constraints.

Peng (21) describes a computer simulator , of a coal preparation plant, developed at West Virginia University. Among other things, it can: calculate and plot washability characteristics of the feed, blend different raw coals, and determine the optimal plant yield for alternate flowsheets (subject to market specifications). In addition to the usual models of processing equipment it contains the semi-empirical flotation model previously mentioned.

2.3.4.3 Economic Simulators

Walters and Ramani (24) developed a computer program capable of predicting the sales revenue of several products (i.e. coarse middling, clean coal, and fine middling) and overall economic efficiency given by:

$$E.E. = \frac{\text{Revenue from simulated separation}}{\text{Revenue from perfect separation}} \quad ...(2.33)$$

It can combine raw coals of different washabilities to form a composite feed, but is limited to a two-stage washing operation at high and low specific gravities (for the coarse and fine portions of the feed). It checks all possible combinations, of the two size fractions washed at varying specific gravities, that will meet up to eight quality constraints. The simulator determines the ten highest yield combinations. The user can then choose the combination of specific gravities

that maximizes revenues.

Zigmond et. al. (39) have developed a computer simulator to determine capital and operating costs for a coal preparation plant. The logic is based on the result of a survey of plant operators, building contractors, equipment manufacturers and consulting firms. An extensive cost-data file for major capital equipment is contained.

The input includes feed size analyses, yields at the designated specific gravities of separation, and the types of washing units desired. The output includes the size of the washing units, and a detailed breakdown of capital and operating costs. The following circuits can be modelled:

1) raw coal storage,
2) crushing and handling,
3) coarse coal cleaning,
4) intermediate coal cleaning,
5) fine coal cleaning,
6) clean coal storage,
7) unit train loading,
8) thermal drying.

Estimated costs are claimed to be accurate to within +30% or -15%.

Peng (30) uses an economic model and a coal preparation plant simulator to obtain capital and operating costs for a proposed coal preparation plant.

If the washability of the feed, the control parameters of the washing units, and the plant configuration are known, the optimum yield can be determined on the basis of maximizing profits, subject to different market specifications. This is often not possible in the real world where ash-price relationships are usually not well defined. One must settle for maximum yield at the product quality specified by the customer. The required selling price to meet a specified discounted cash flow rate of return (DCFROR) can also be determined.

## 2.4 OTHER OPTIMIZATION METHODS

### 2.4.1 LINEAR PROGRAMMING

Linear programming is a way of determining the most favourable allocation of a resource (wood, milk, coal, etc.) in a systematic manner (40). This is done by constructing a linear optimization model and determining the optimal solution (maximizing or minimizing the objective function) which satisfies all the constraints. The objective function could be to maximize profits or minimize costs, depending on the problem at hand. Their constraints can include such things as market requirements, production capacity, available resources, and blending limitations. If the linear programming model is complex, with a large number of equations, a computer must be used for its solution. Many excellent books are available on the subject of which

Wagner's (40) publication is but one example.

For coal, if the choice of products is reasonably large and the number of constraints are not great, linear programming can be used to obtain the most profitable combination of products and blends. If there is little or no choice, the problem solves itself and linear programming is of no value.

Wright (41) used linear programming to determine the most profitable product combination from a coal preparation plant. His constraints included market requirements for different products and blends, production capacity for different products, blending proportion limitations, quality specifications, production costs, and prices.

In Wright's example where the optimal solution included 30 different products and blends, linear programming was a useful tool. However, production costs per tonne of clean coal, for different feeds at different ash levels, must be known. This requires a good understanding of the clean coal ash-yield relationships for each coal being processed.

In the western Canadian coal industry, the choice of products is either very small (2 or 3) or does not exist and operators must produce to customer specifications in an optimal manner. There is no room for flexibility; consequently, no possibility for optimization through linear programming.

The modelling of coal processes using linear programming is not practical (or very limited) since the

relationships between yield and quality for processing units are not linear.

### 2.4.2 BLENDING

The controlled blending of raw coals from different seams, with different washing and quality characteristics, is necessary to ensure proper plant performance and consistency of product. This is especially true in the case of metallurgical coals because caking properties such as fluidity, F.S.I., and dilatation are inherent with specific seams. As mentioned in the discussion of linear programming, product blending is also important to meet given market requirements in an optimal manner.

Blending can be carried out through the use of open stockpiles or silos. European plants have traditionally used large raw coal homogenization bunkers to provide a consistent feed thus optimizing yield. Firth et. al. (27) refer to the blending of raw coals on the basis of "good and bad" washing characteristics to obtain acceptable yields on a regular basis.

Butcher and Beninger (42) claim that the key to achieving optimum yield is to maintain a constant cut point in the plant processes. If this is done there is no difference in overall yield whether the blending takes place before or after washing. This is only true in theory.

In a typical multi-seam mine, individual seams are released in a sporadic manner. Even when raw coal stockpiles

(or silos) are used, a consistent distribution of seams that agrees with their long-term distribution is not possible on a regular basis. To attempt to wash different coals individually at a constant cut point (obtaining different product ash levels) and to blend the products in a constant manner to maintain the overall ash specifications would be a logistics nightmare.

Plant operators typically try to minimize the fluctuations in raw coal blends such that cut point adjustments in the plant are minimized while maintaining the required ash level. At Line Creek the idea of seam blend optimization is being utilized. This means that for a given supply of raw coals from several seams, an optimum blend is processed such that yield is maximized while meeting all required quality, production, and blending constraints.

### 2.4.3 M CURVES

The M curve (Mayer curve) is a method of plotting float-sink results to predict the cleaning characteristics of coals. The curve is not widely used because graphical interpolation from it is typically less accurate than from standard washability curves.

If the ash content of clean coal and refuse are specified, the yields of clean coal and middling and the ash content of the middling, for a perfect separation, can be determined from the curve. The construction and interpretation of M curves are well described in reference

(3). Figure 2.7 gives an example of an M curve - $X_1$ represents the clean coal ash content, Y is the clean coal yield at ash content $X_1$, and $X_2$ is the raw coal ash content.

M curves can be used to predict optimum coal product mixtures when mixing unwashed coals with washed coals (it would be interesting to compare results obtained from the M curve with the maximum yield principle for Figure 2.5). It can also be used to determine the common cut point at which to wash different coals such that the combined products meet a specified ash level, at a maximum yield. It should be noted that this agrees with the constant cut point principle of optimum yield mentioned by Butcher and Beninger (42).

Salama (43) presents graphical methods based on M curves to determine the optimal cut points for a blend of raw coals, to achieve maximum yield at a given clean coal level. They can be used easily with up to three different coals. For a greater number of coals numerical optimization techniques using a computer are suggested.

Bowen et. al. (44) make use of the M curve in their computer program for the optimization of flowsheet design. The design objective is to maximize yield at a given clean coal ash level by applying the incremental ash principle for washers in parallel. The M curve is fitted by a conic section equation. It can thus be manipulated to give the raw coal ash, the incremental ash, the target ash, and the ash at zero yield, thus covering the full range of values. To estimate actual results in imperfect washers, the curves are

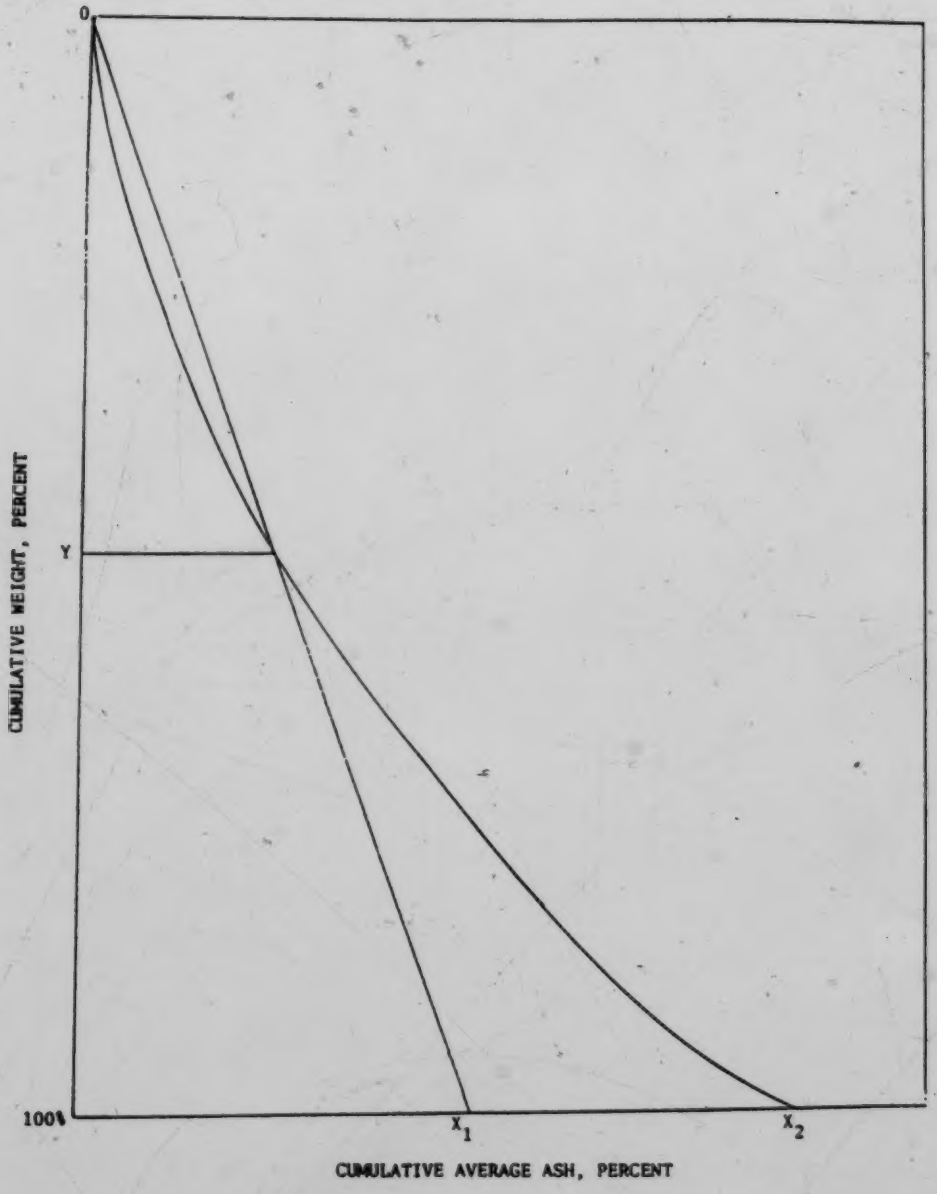



Figure 2.7 A Mayer Curve or M Curve

modified by applying distribution curve data. Bowen et. al. report a good correlation between yield and ash results calculated by their program and hand-calculated results.

## 2.5 PROCESS CONTROL AND AUTOMATION

### 2.5.1 MOTIVATION FOR BETTER PROCESS CONTROL

Once the required set points, to achieve an optimum level of cleaning, in each constituent circuit in a coal preparation plant are determined we must maintain those set points such that ash fluctuations are minimized. This practice is termed process control.

Ash fluctuations, measured by the variance of instantaneous ash, are caused by disturbances which are described as follows:

1) intrinsic disturbances due to changing characteristics of the coal such as washability and size distribution,
2) extrinsic disturbances due to changes in the process such as media specific gravity and other control variables.

Extrinsic disturbances can, therefore, be minimized by optimizing process control.

There are two main reasons for minimizing instantaneous ash variance. The obvious one is to not exceed customer specification. A more subtle reason, and typically not well understood by many operators, is that yield (production) is lost every time the instantaneous ash value deviates from

the process average. Plitt and Flintoff (16) present a straightforward means of determining these losses. In their example, a reduction of 94% in the variance of the instantaneous ash results in a yield gain of 2.3%. Calculations carried out with Line Creek data show losses in the range of 2 to 3% as a result of ash variations. Plitt and Flintoff (16) also present methods for the estimation of yield increases through variance reduction and the estimation of the potential reduction in ash variance (through the use of a variance spectrum).

Most operators control product ash at a level below market specification to minimize the possibility of exceeding those specifications. By reducing the variance of the instantaneous ash, the ash limit can be more closely approached (incurring a yield gain) without increasing the possibility of exceeding it.

If a 2% yield gain is assumed, the additional production, for a plant producing 2,000,000 tonnes of metallurgical coal annually, would be approximately 57,000 tonnes (using a yield of 70%). At a price of $40.00 per tonne (after subtracting shipping costs) this represents an increased cash flow of $2,280,000 annually. Even if this figure is optimistic, its magnitude is an excellent motivator toward optimizing process control.

Other important applications of process control include monitoring and metering of consumables, such as flocculants, to minimize costs; and controlling levels in flotation cells

and sumps to prevent coal losses and minimize costly process interruptions.

### 2.5.2 DIFFERENT PROCESS CONTROL SYSTEMS

The different process control systems can be summarized as follows (taken from descriptions given by Salama et. al. (45)): Analog control is the earliest and simplest system and is common in Canadian coal preparation plants. The measured process variables are compared with predetermined set points and the error signals drive the analog controller. These systems are difficult to calibrate and maintain because the analog components are subject to electrical drift.

Analog control with a supervisory computer is an analog system connected to a digital computer. It can collect and store data and carry out some process modelling. Unlike simple analog control, in that it automatically determines proper set points based on given criteria, these systems tend to be complex (due to the analog-digital interface) and expensive. They are not widely used.

Analog supervisory computer set point control is where many of the control functions are determined by the process computer and implemented automatically.

Direct digital control systems utilize a central process control computer to perform most of the functions of the local controllers in analog systems. These systems are more reliable, offer more flexibility, are easier to

service, and are simpler to operate than analog systems. However, if the central control computer fails, the central control functions are lost.

Distributed microprocessor supervisory control systems overcome the lack of back-up problems posed by direct digital control systems. In a distributed system the process control functions are spread over several control computers or microprocessors which can be interfaced with a supervisory digital computer. The distributed system has the back-up typical of an analog system and all of the advantages of a digital system. It is expected that this type of system will see more widespread use in the future.

### 2.5.3 AUTOMATION

Automation is an integral part of process control optimization. It implies the monitoring and control of process variables without human intervention. This has several advantages:

1) monitoring is constant; thus, if the system is properly tuned, the action taken should be the best possible for a given set of operating conditions;
2) actions taken are consistent, not open to human interpretation or neglect;
3) significant labour savings are usually involved.

Recent developments include the use of nuclear density gauges for specific gravity monitoring and control in heavy media systems (widely used in Canadian coal preparation

plants).

A further development of this concept is the use of on-stream ash analyses to control specific gravity settings in a heavy media system, thus minimizing deviations from the desired ash level. This has been done successfully in Australia (46) where an on-stream ash analysis signal is used, through a computer, to automatically adjust the set points of four heavy media circuits.

Lyman and Denney (47) report the development of a microprocessor-based controller for the control of flocculant addition to a thickener, using the signal from a turbidity sensor. It can be used in conjunction with a nuclear gauge to measure underflow density, and a varible speed thickener underflow pump to optimize thickener operations while minimizing flocculant costs.

A principal candidate for process control and automation is froth flotation of coal. Mikhail et. al. (48) point out that losses through fine coal cleaning units, including flotation, account for 83% of all coal losses from Canadian coal preparation plants. This is quite alarming since fine circuits typically contribute only 15 to 30 percent to the overall product. Clarkson et. al. (49) claim to have achieved automatic flotation control (in Australia) using a prototype on-stream slurry analyzer to measure ash and percent solids. It sequentially analyzes the feed, product, and tailing streams and uses these signals to control cell level and reagent addition. It thus attempts to

maximize yield while maintaining a specified ash level. They claim to have achieved a 10% improvement in flotation yield while maintaining a more consistent product ash and percent solids.

Another possible application of on-stream coal analyses is for the on-stream blending of thermal coals (by a utility company for example). It has been suggested (50) that through on-line analyses the exact content of sulfur and/or ash in the blend can be determined as the blend is being created. The ratio of the lower quality (usually cheaper) coal can therefore be maximized automatically while not exceeding the specified limits. This results in economic gains.

### 2.5.4 ON-STREAM COAL ANALYZERS

In recent years an increasing number of on-stream coal analyzers have become available with a wide range of capabilities, for slurry and solid stream. Plitt and Flintoff (16) present a good summary of the different methods available. They can be categorized as follows:

| TYPE | APPLICATION |
|---|---|
| Neutron Activation Method | Solids |
| Transmission Method | Solids and Slurries |
| Backscatter Method | Solids and Slurries |

The principal variables measured are total ash, percent solids (slurries), sulfur, and ash components. In the case of solids, calorific and moisture values can also be

determined if nuclear magnetic resonance, coupled with electron spin resonance, methods are used (51).

In general, these units tend to be expensive (in the range of $80,000 for moisture analyzers and $150,000 and up for ash and ash component analyzers) and some operating problems have been encountered, such as correcting for Fe content. Nevertheless, it is the belief of the author that they have great potential in process optimization for the following reasons:

1) results in a more consistent product quality;
2) allows yield maximization through the reduction of instantaneous ash variance (also allows for a reduction of the ash "safety margin", thus incurring a yield increase);
3) allows full and constant exploitation of the incremental ash principle for optimum yield.

## 2.6 THE SYNTHESIS OF A PRACTICAL OPTIMIZATION STRATEGY AT LINE CREEK

Early operating experience demonstrated that plant yields and clean coal ash levels are very sensitive to feed blends. The reasons for this are graphically presented in Figure 2.8. Each seam exhibits an overall washability $W_i$, which is a function of its inherent washability $w_i$ with no dilution (d=0) and the amount of dilution, d, picked up during mining. The latter can include rock from beyond the seam boundaries and/or thin waste partings within the seam

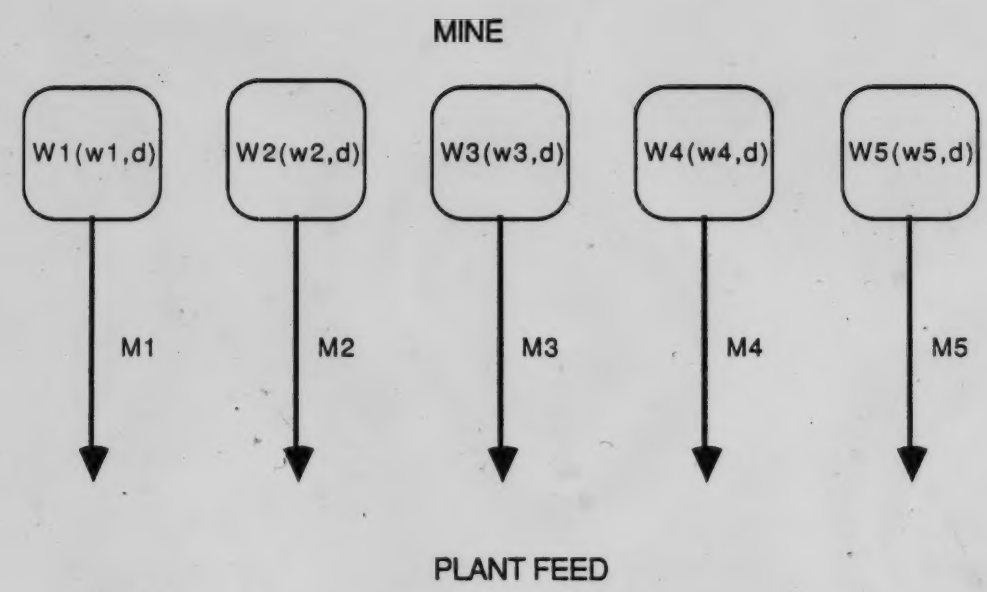



Figure 2.8 Graphical Representation of Seam Distribution and Washabilities

which cannot be economically mined. Wi is, therefore, a variable determined by nature and mining technique;

$$W_i = f(w_i, d) \qquad \ldots(2.34)$$

where: $W_i$ = observed washability
$f(\ldots)$ = some functional relationship
$w_i$ = inherent washability of the coal seam
$d^i$ = a measure of coal seam dilution as a result of the mining operation

$M_i$ represents the amount of each seam delivered to the plant over a specified period. In the long term $M_i$ is determined mainly by nature but in the short term it is a function of mine planning.

The varying seam quantities and washabilities must be accommodated through the plant such that a specified clean coal ash is maintained. To do this the correlations between raw coal ash, clean coal ash, and yield, through the plant, must be determined for each seam.

Much of operating data were examined to accomplish this. It was found that each seam had a characteristic yield which varied with raw coal ash and clean coal ash. A series of linear equations, one for each seam, was derived to estimate yield; given the raw coal ash of each seam and the overall clean coal ash. The overall yield was calculated from a weighted average of the seams present in the feed. The equations, given in Table 2.3. proved useful for explaining plant performance and for budgeting purposes. Results were acceptable in the long term and over narrow ash ranges, however, much greater accuracy was required on a

Table 2.3 Yield - Ash Correlations and Prefered Seam Blending Targets for the Major Coal Seams

Yield-Ash Correlations

| SEAM | |
|---|---|
| #7 | Yield = 45 - (R.C. ash - 38) + 2 (C.C. ash - 9.5) |
| #8 | Yield = 80 - (R.C. ash - 20) + 2 (C.C. ash - 9.5) |
| #9 | Yield = 65 - (R.C. ash - 22) + 2 (C.C. ash - 9.5) |
| #10B | Yield = 60 - (R.C. ash - 35) + 2 (C.C. ash - 9.5) |
| #10A | Yield = 42 - (R.C. ash - 25) + 2 (C.C. ash - 9.5) |

Steam Blending Targets

| SEAM | #8 (%) | #7 (%) | #9 (%) | #10A/10B (%) |
|---|---|---|---|---|
| | 30 | 0-30 | 30-70 | 0-40 |
| Most Favourable | 40 | 0-40 | 10-60 | 0-40 |
| Range | 50 | 0-50 | 0-50 | 0-40 |
| | 60 | 0-40 | 0-40 | 0-40 |

day-to-day basis.

The general blending guideline is also given in Table 2.3. The acceptable blends are given for varying levels of #8 seam (the main seam). The feed blend was chosen such that the combination added up to 100%, for example: 40% #8 seam, 30% #7 seam, 30% #9 seam, and no #10A and/or #10B seams. The intent was to process a feed blend which would give an acceptable clean coal ash level with an acceptable yield. Although the guidelines eliminated many unacceptable combinations, it left a lot of room for guesswork and the resulting blend was not necessarily optimal.

A more exact understanding of the behaviour of each seam through the plant was needed to accurately estimate yields and optimize blends. This was gained through plant trials during which each seam was processed separately and all process streams were sampled. The results provided a wealth of information on each process circuit and identified problem areas. It also formed the basis of the plant simulator.

The simulator allows accurate calculation of plant yields given feed blends, individual seam raw coal ashes, and clean coal ash results. It is used to rationalize plant yield results and to predict future yields. It is also used to identify optimum seam blends given seam availabilities and the raw coal ash of each seam. The recommended blends are subject to the following constraints:

- meeting target ash,

- meeting target F.S.I.,
- blending consistently with available reserves,
- meeting required production levels.

The simulator is not universal - it is specific to the five seams processed through the Line Creek coal preparation plant. However, the principles and methodology described can be applied to construct other simulators for other coals and other plants. The expected degree of success will depend upon the raw coal storage and blending facilities.

## 3. EXPERIMENTAL METHODS AND SUMMARY OF RESULTS

### 3.1 DESIGN OF EXPERIMENTS (PLANT TRIALS)

To determine the behaviour of each seam through the plant individual seam plant trials were carried out. The purpose of the plant trials was to:

1) characterize the behavior of all seams through each process circuit;
2) determine the relationships between raw coal ash, clean coal ash, and plant yield;
3) determine the performance of each process circuit with respect to particle size;
4) identify problem areas requiring attention, such as low efficiency or poor quality;
5) help determine which process streams to monitor, to optimize process control;
6) determine required process instrumentation;
7) provide the data required to construct a computer simulator of the plant to accurately calculate plant yields, and recommend optimal feed blends.

A total of five plant trials were carried out, one for each seam. During the trials:

1) each seam was processed separately under steady state conditions;
2) all 16 process streams were sampled, at 20 minute intervals (except the plant product), for a three hour period;

3) individual cuts were combined to obtain an unbiased composite sample of each stream for the three hour period;
4) each sample was analyzed for ash, F.S.I. and moisture (where appropriate);
5) each sample was screened at 6 mm, 28 M, 100 M, and 200 M, and each size fraction was also analyzed for ash and F.S.I.;
6) washability analyses were done on heavy media cyclone products and rejects to derive distribution curves.

Figure 3.1 gives the plant flowsheet location of all sampling points. Wherever possible (where accessible) total stream cuts were taken. A three hour trial duration was estimated to be the maximum allowable without adversely affecting clean coal quality and production. The 20 minute sampling interval was the minimum that would permit the sampling team sufficient time to collect all of the samples. The objective was to collect as many cuts of each stream as possible within the limits imposed by the process and manpower available.

Detailed descriptions of all samples and sampling points are given in Appendix 1 (section 7.1). It is worth noting that the H.M. cyclone feed, product and reject samples satisfy A.S.T.M. requirements (document D2234(52)) for the number of increments and sample size. Some of the slurry samples, such as the secondary water-only cyclone product, provided relatively small samples due to the very

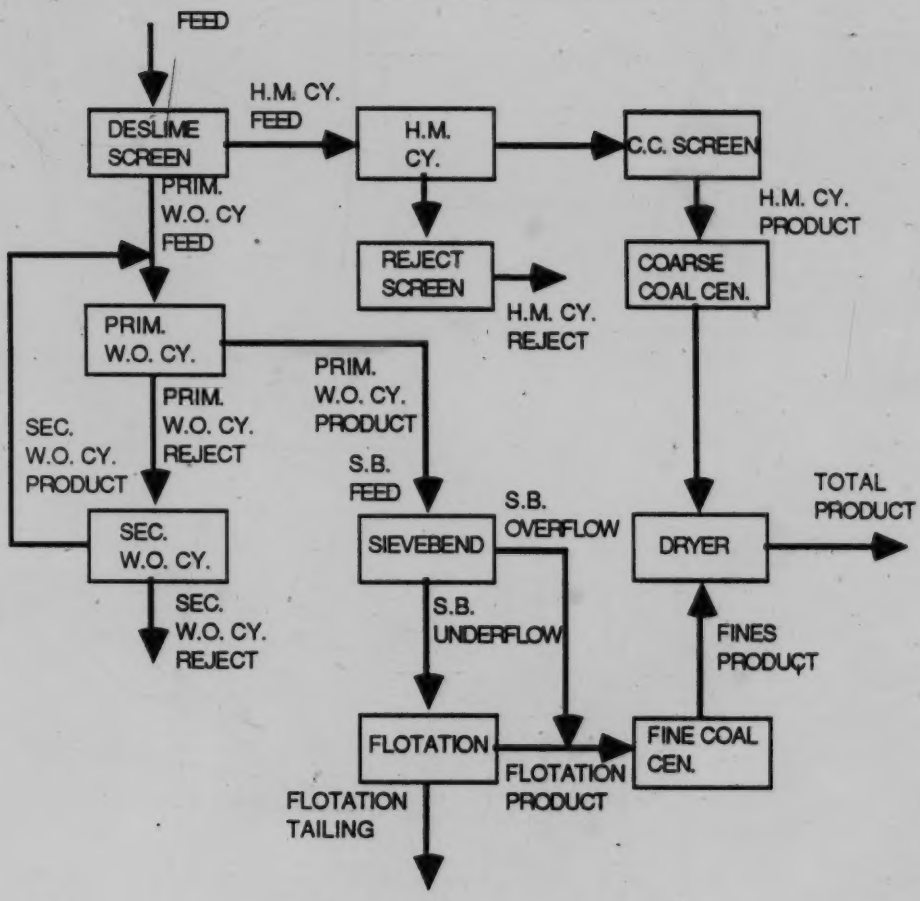



Figure 3.1 Plant Trial Flowstream Sampling Locations

dilute nature of these slurries.

### 3.2 EXECUTION OF EXPERIMENTS

It is standard practice at Line Creek to store only one seam in a specific raw coal silo, whenever possible. This permits much better control of raw coal blending and facilitates the performance of the plant trials. Each trial was carried out on a day when a sufficient amount of a given seam (at least 2000 tonnes) was available in one of the silos, to ensure uninterrupted operation for a period of 3.5 hours. The raw coal ash and F.S.I. for each seam had to be typical of that seam.

Sampling was started after each seam was processed for one half hour. This *warm-up* period was necessary to:

1) ensure steady state conditions,
2) ensure that all other seams previously processed had left the plant.

During each trial:

1) the plant feed rate was maintained constant at approximately 400 tonnes per hour,
2) heavy media specific gravity was maintained constant,
3) flotation reagent addition (Kerosene and MIBC frother) were adjusted regularly (as per normal practice) by the operator to maximize flotation yield.

All sampling was done by the same individuals (the Quality Supervisor, the Senior Analyst and the author). Specific samples were always taken by the same person to

ensure consistency in procedures and allow familiarization with each sampling point.

The trials were spread out over an eight month period to:

1) accommodate the availability of each seam in the required quantity,
2) not interfere with regular production,
3) not create an unmanageable backlog of samples in the laboratory since all work was done without the procurement of additional manpower.

The trials were carried out in the following sequence:

| SEAM | DATE PERFORMED |
|---|---|
| #7 | May 10, 1985 |
| #10A | June 13, 1985 |
| #8 | September 10, 1985 |
| #10B | September 28, 1985 |
| #9 | December 6, 1985 |

### 3.3 PROCESSING OF SAMPLES

Sample preparation was carried out according to the flowsheet in Figure 3.2. All samples were dried at 40° C for 24 hours to determine % solids (by weight) for slurries or air dry loss % moisture where appropriate (refer to detailed results in Appendix 1).

Samples were then riffled to representatively reduce them to a manageable size. Very large samples, in excess of 100 kg, were coned and quartered prior to riffling.

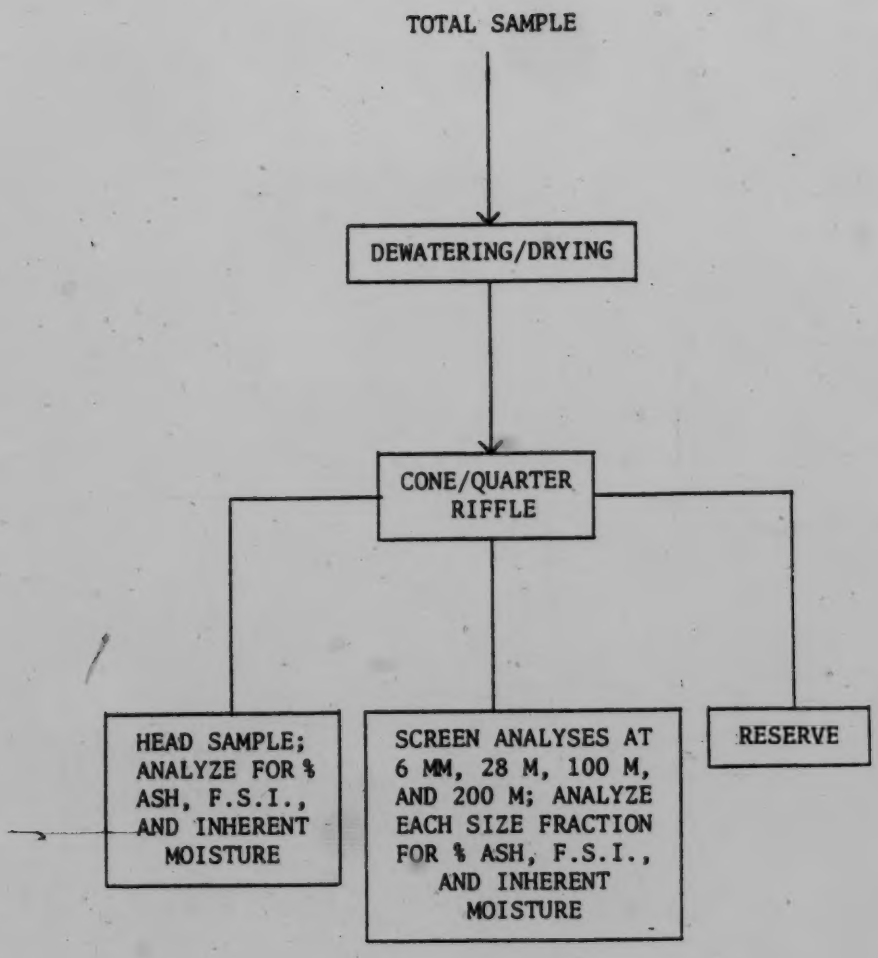

TOTAL SAMPLE
DEWATERING/DRYING
CONE/QUARTER RIFFLE
HEAD SAMPLE; ANALYZE FOR % ASH, F.S.I., AND INHERENT MOISTURE
SCREEN ANALYSES AT 6 MM, 28 M, 100 M, AND 200 M; ANALYZE EACH SIZE FRACTION FOR % ASH, F.S.I., AND INHERENT MOISTURE
RESERVE

Figure 3.2 Sample Preparation and Analysis Scheme

Each head sample was analysed for ash, F.S.I. and inherent moisture. A second portion was screened at 6 mm, 28 M, 100 M, and 200 M. The weight frequency of each size fraction was determined and each fraction was analysed for ash, F.S.I. and inherent moisture. The third portion (reserve) was stored.

All analyses were done in duplicate, according to A.S.T.M. standards (52), by the Senior Analyst at the Line Creek laboratory.

Washability analyses were carried out on heavy media cyclone products and rejects to derive distribution curves and to construct washability curves for the reconstituted feed.

### 3.4 RESULTS

The detailed results of all plant trials are given in Appendix 1 (sections 7.2 → 7.6). A summary is presented here. All yields are calculated via the two product formula using the ash analyses on a dry basis. The need to balance[1] the data prior to yield determination was not seen as necessary since ash is the only component that can be used to calculate the yield, i.e.

1) water is added in varying and unmeasured quantities throughout the circuit, precluding the use of moisture analyses,

2) the coal will undergo in-line size degradation which

---

[1] i.e. reconcile using a least squares data adjustment procedure.

precludes the use of size consist data in the calculations,

3) F.S.I. is not a linear property, i.e. blending two coals of different F.S.I. will not necessarily produce a mixture with an arithmetic average F.S.I.

### 3.4.1 TRIAL WITH #7 SEAM

The main features of #7 seam are (refer to Figure 3.3):

1) it exhibits very low flotation yield at about 18% (the lowest of all the seams;
2) it shows a significant loss of coal through flotation, indicated by a flotation tailing F.S.I. of 4;
3) it cannot meet the specified plant product ash of 9.50% even at very low heavy media specific gravities;
4) the ash level in the sievebend oversize is too high, and it has a negative impact on plant product ash.

### 3.4.2 TRIAL WITH #8 SEAM

The main features of #8 seam are (refer to Figure 3.4):

1) it exhibits the highest yield, through flotation, at about 84%. This is accomplished with a flotation product ash that is within the acceptable range.
2) it can easily be processed to achieve the desired plant product ash level.

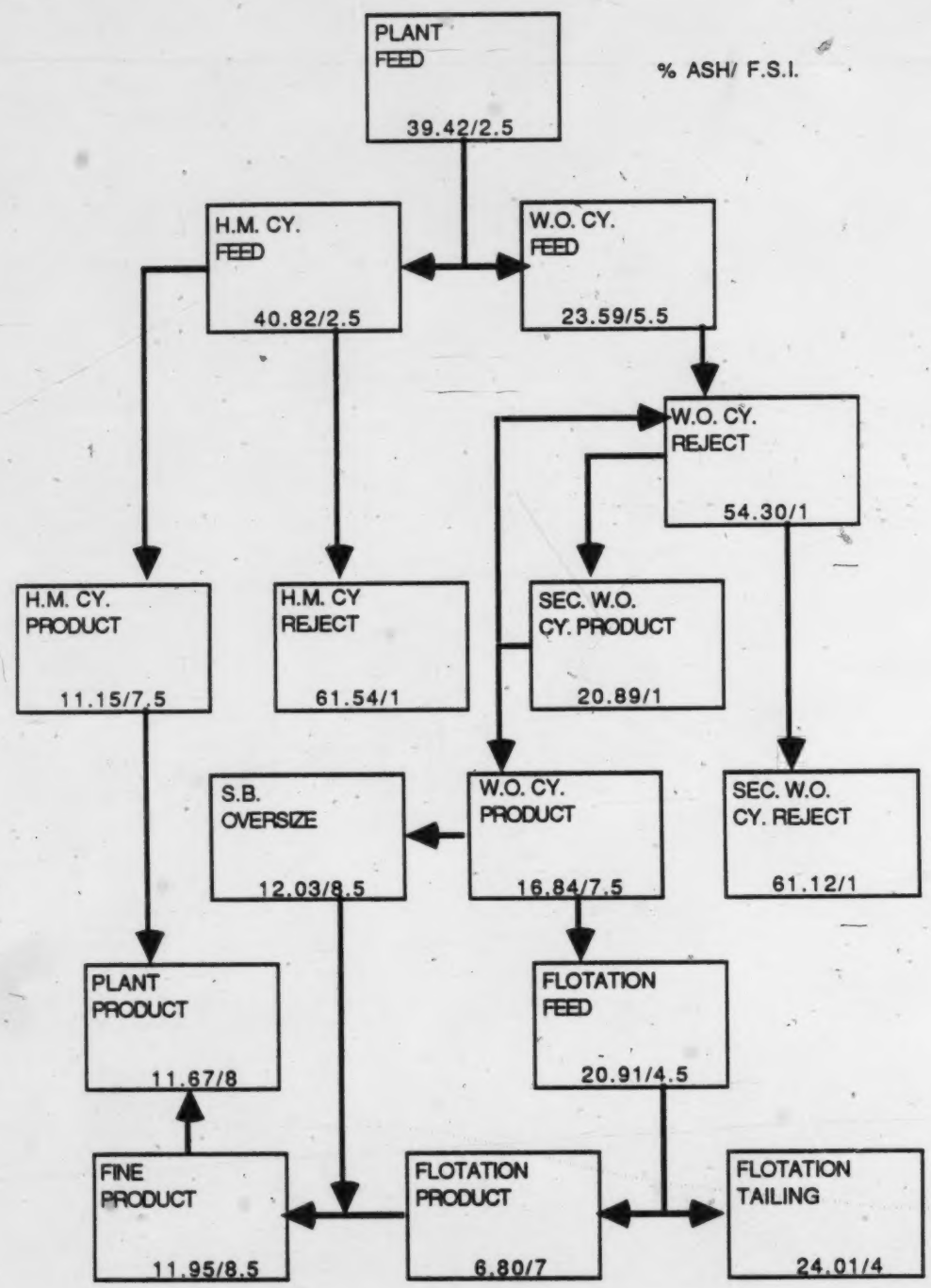



Figure 3.3 Material Balance Results For #7 Seam

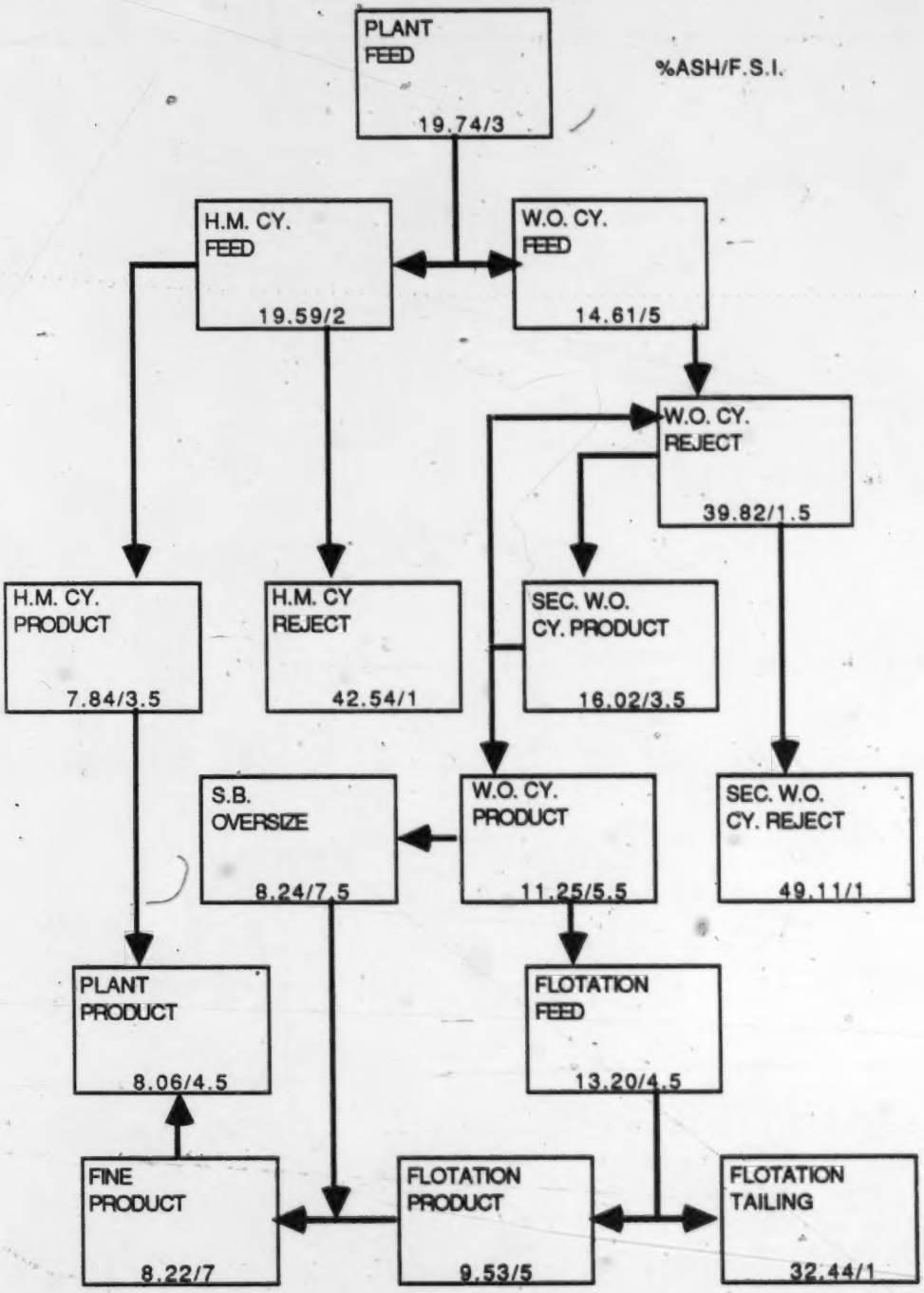



Figure 3.4 Material Balance Results For #8 Seam

### 3.4.3 TRIAL WITH #9 SEAM

The main features of #9 seam are (refer to Figure 3.5):

1) it performs poorly through flotation with a yield of about 49%,
2) it shows a significant loss of coal through flotation, indicated by a flotation tailing F.S.I. of 4;
3) like #8 seam, it can easily be processed to achieve the desired plant product ash level.

### 3.4.4 TRIAL WITH #10B SEAM

The main features of #10B seam are (refer to Figure 3.6):

1) it exhibits an acceptable flotation yield of about 61%, and flotation losses are not as significant as with seams #7, #9 and #10A;
2) it cannot meet the specified plant product ash, even at very low heavy media specific gravities;
3) the ash level in the sievebend oversize is too high.

### 3.4.5 TRIAL WITH #10A SEAM

The main features of #10A seam are (refer to Figure 3.7):

1) it exhibits very low flotation yield at about 37%;
2) it shows significant flotation losses with a flotation tailing F.S.I. of 5.5;
3) it cannot meet the specified plant production ash (it has the highest heavy media cyclone product ash of all

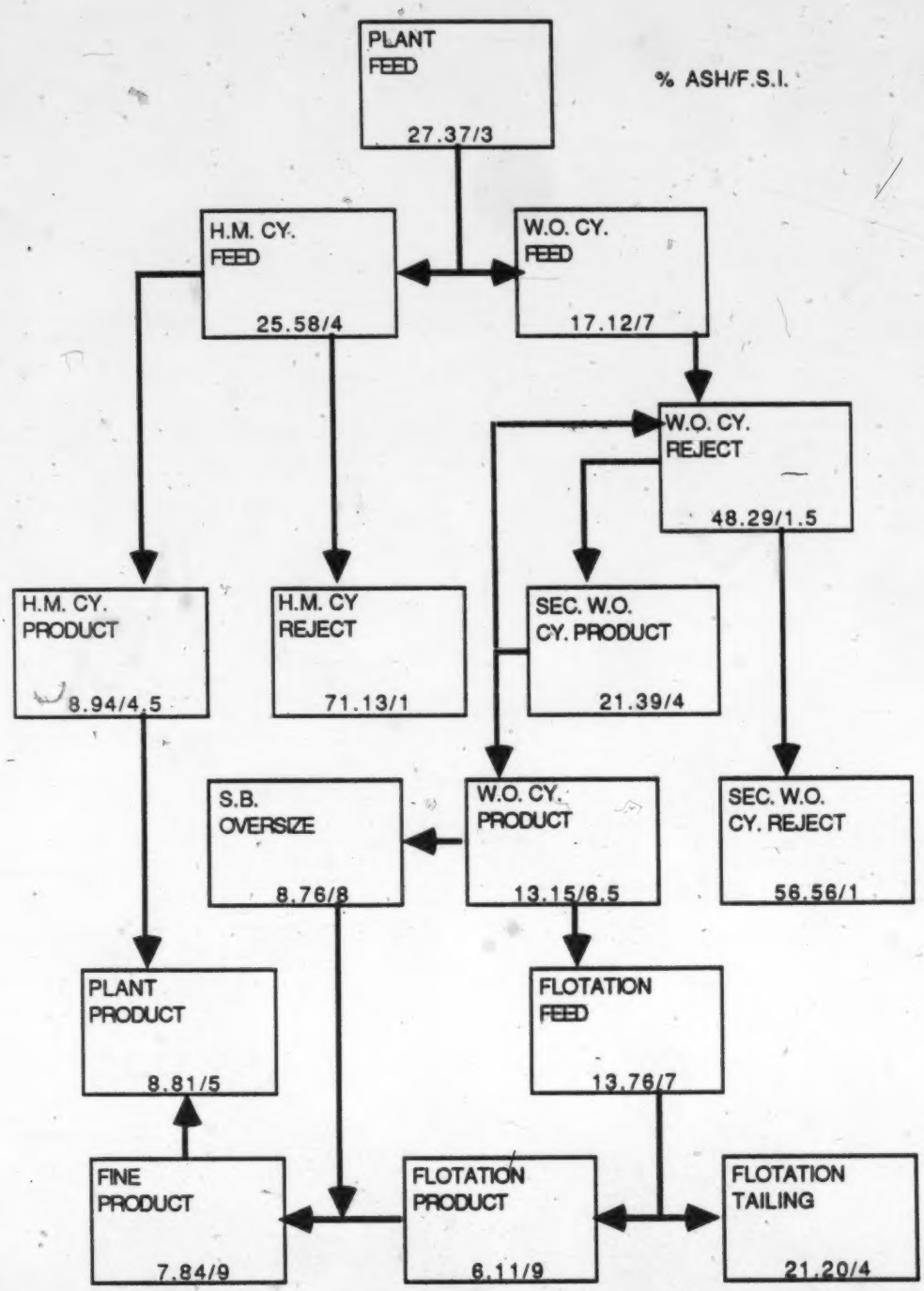



Figure 3.5 Material Balance Results For #9 Seam

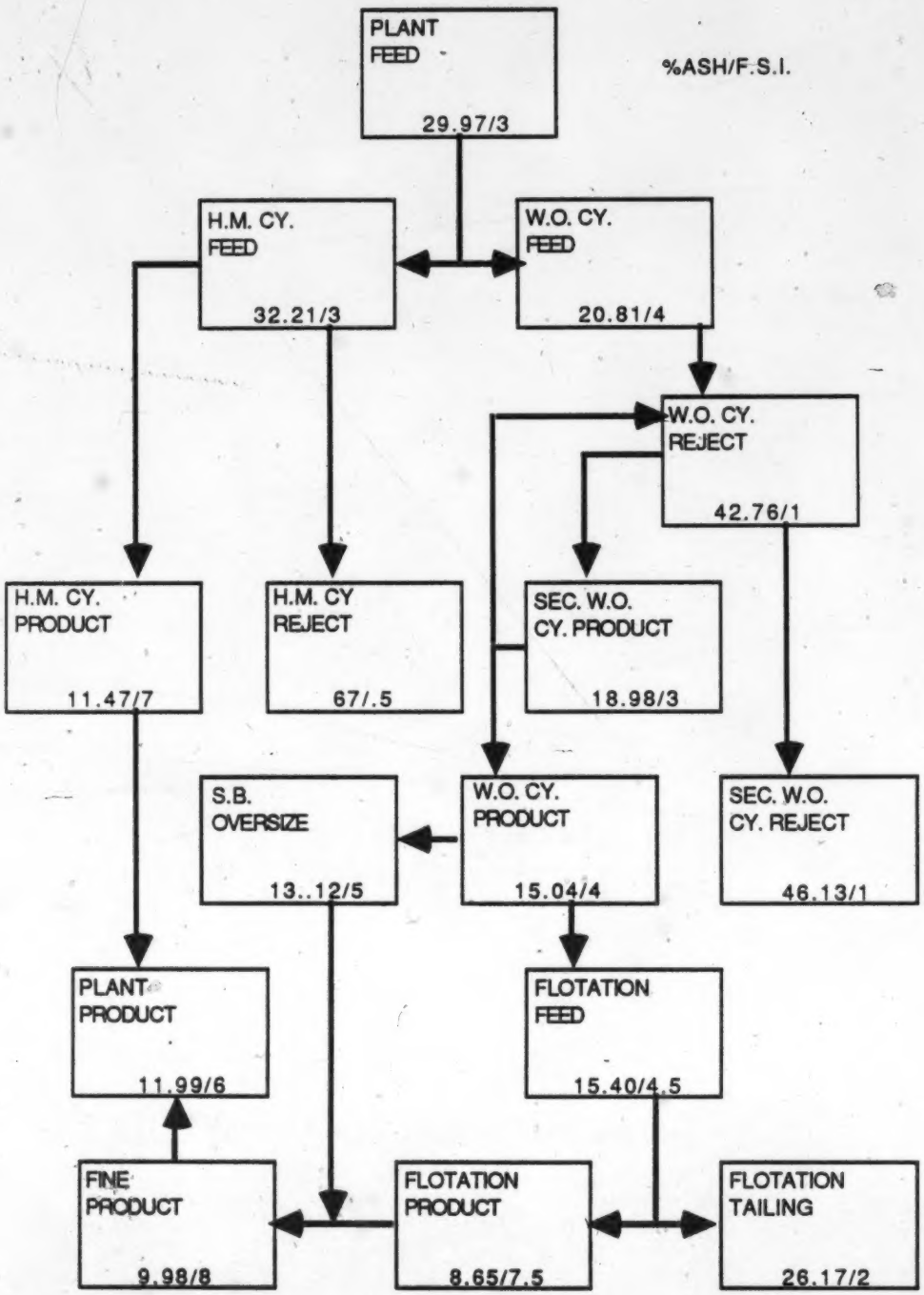



Figure 3.6 Material Balance Results For #10B Seam

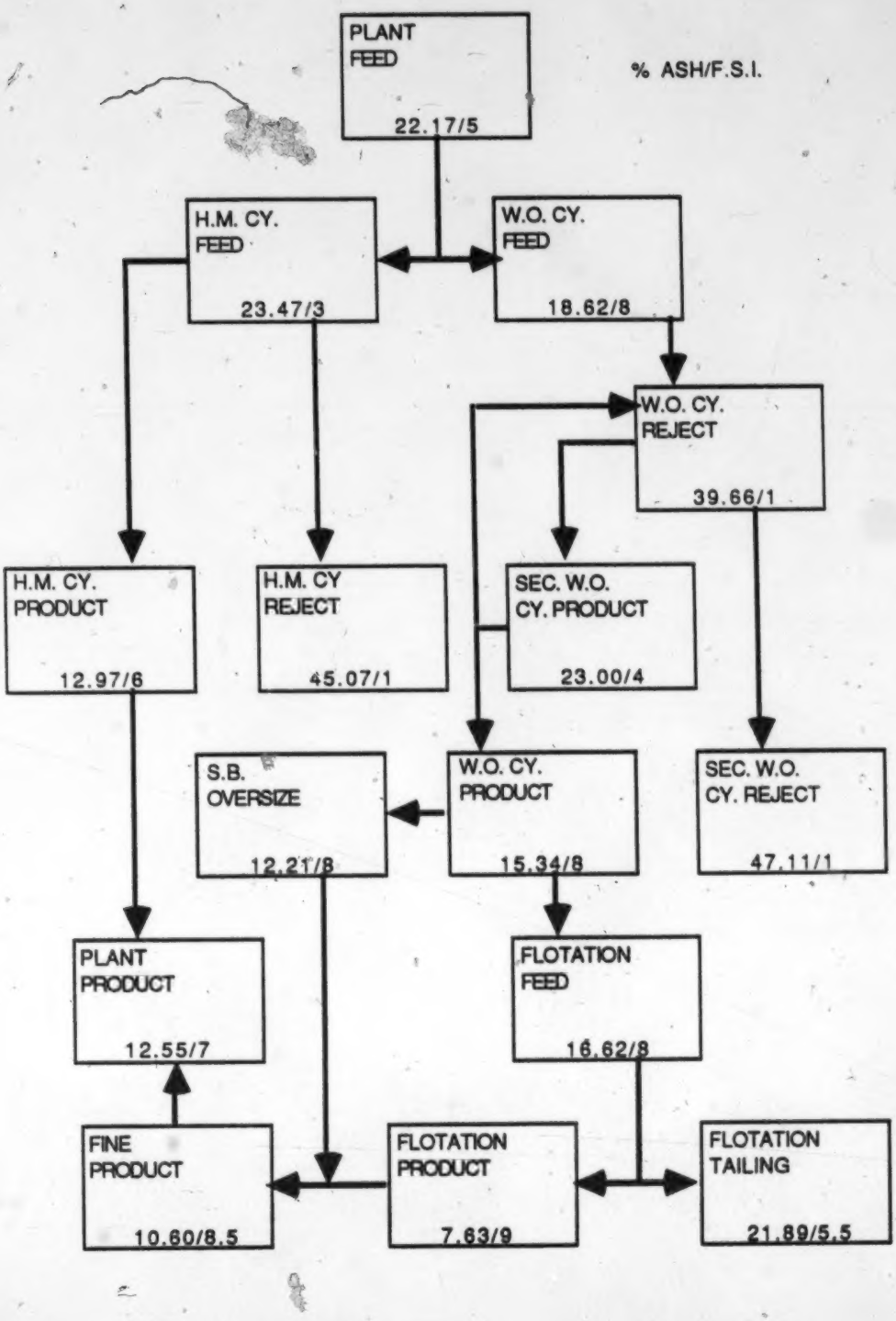



Figure 3.7 Material Balance Results For #10A Seam

the seams in spite of being washed at the lowest possible heavy media specific gravity);

4) the ash level in the sievebend oversize is too high.

### 3.4.6 GENERAL COMMENTS

In the case of seams #7, #10B and, to a much lesser extent #10A, (refer to Appendix 1) the high ash level in the sievebend oversize is partially a result of the carry-over of high ash fines. However, the main factor appears to be the inability of the water-only cyclones to adequately wash the 28 M (mesh) by 100 M fraction.

As expected, for the heavy media cyclone circuit, Ep's are relatively constant for all seams and range from 0.035 to 0.040. This is a little high and probably results from measuring all four cyclones, thus, the average result (unless they are operating at exactly the same cut point) will be a little higher than the individual results. In practice factors such as: specific gravity of the media, cyclone feed pressure and throughput are not exactly the same in all cyclones in a circuit and the individual cut points vary slightly.

Figures 3.8 to 3.12 show that all seams have significant by-pass of high specific gravity material (in the range of s.g. $\geq$ 2.2) of 1 to 2%. The impact of this material on the product ash becomes more and more significant as the yield through the heavy media circuit drops. It is one of the reasons why Seams #7, #10B and #10A

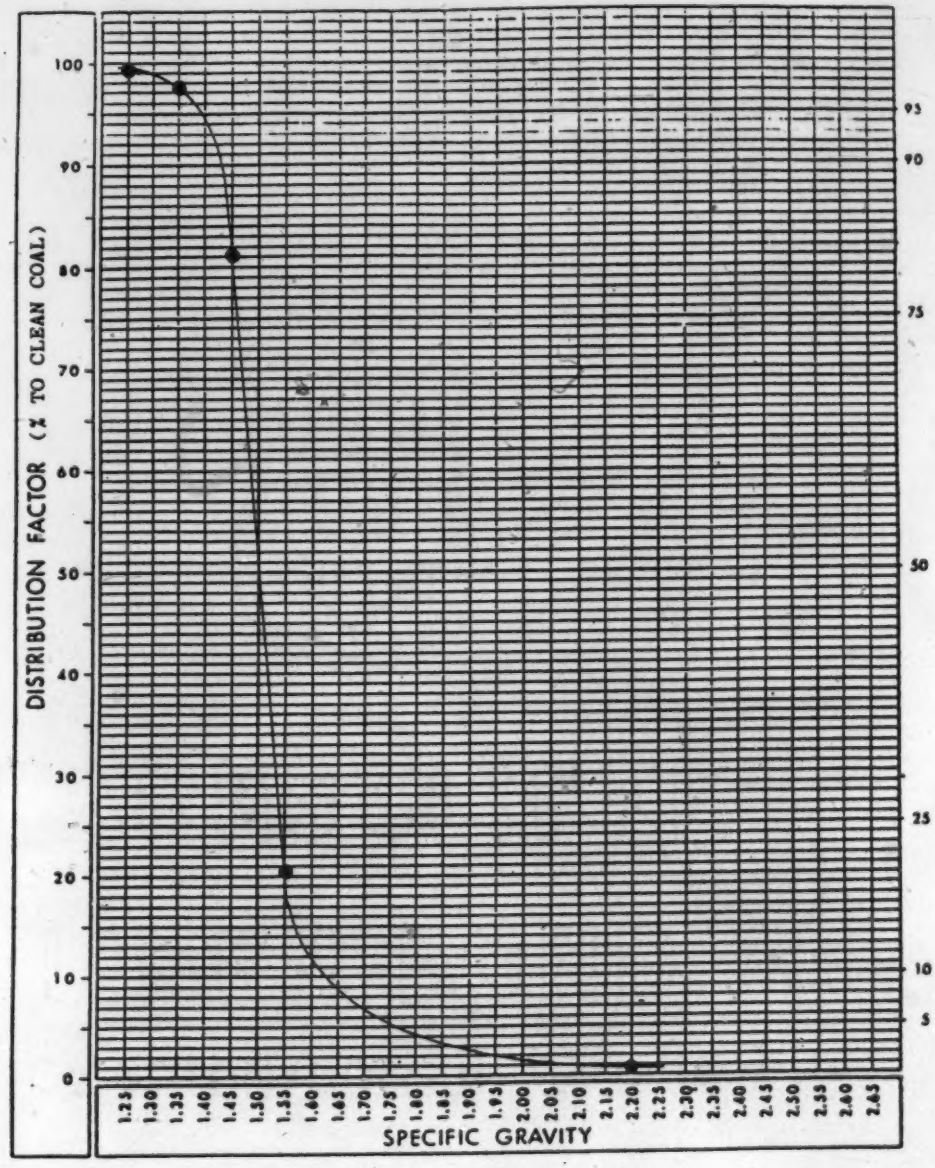



Figure 3.8 Heavy Media Separation Distribution Curve for #7 Seam

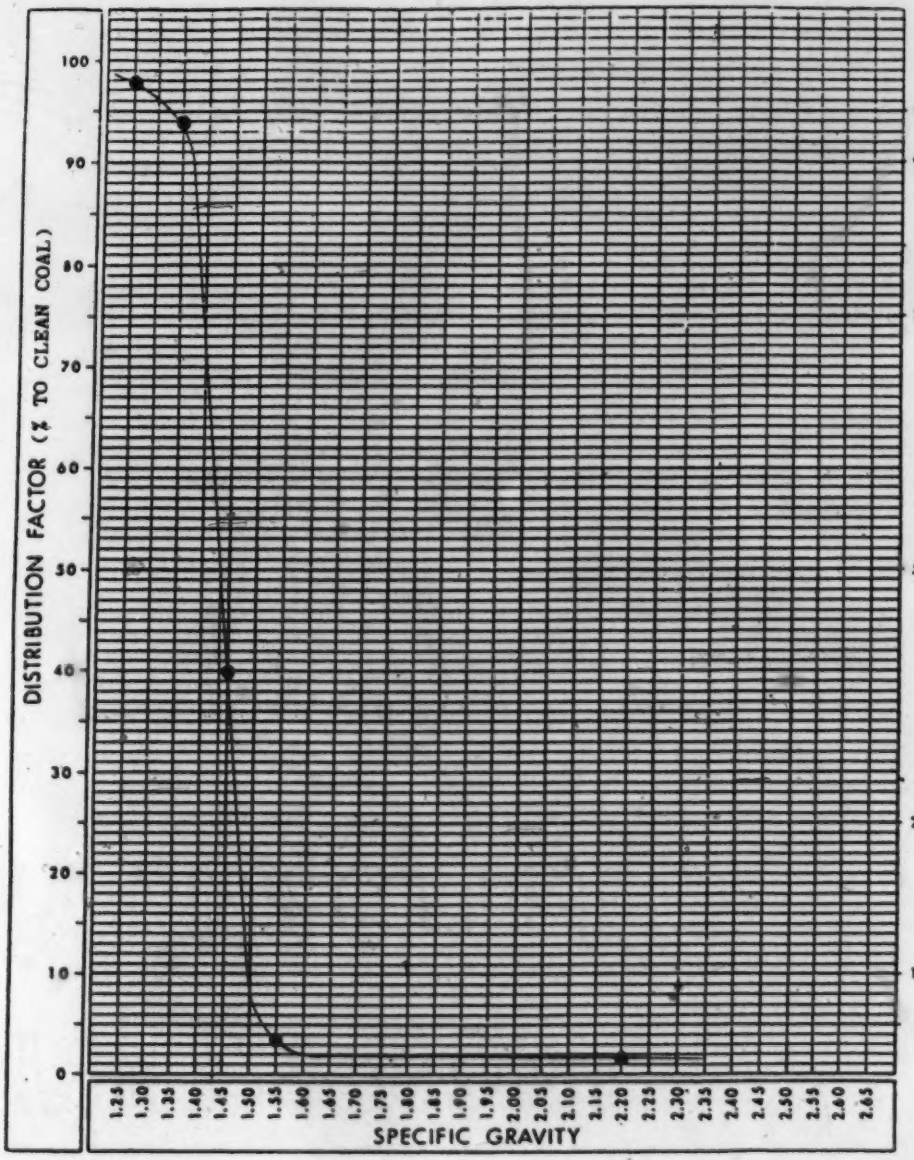



Figure 3.9 Heavy Media Separation Distribution Curve for #8 Seam

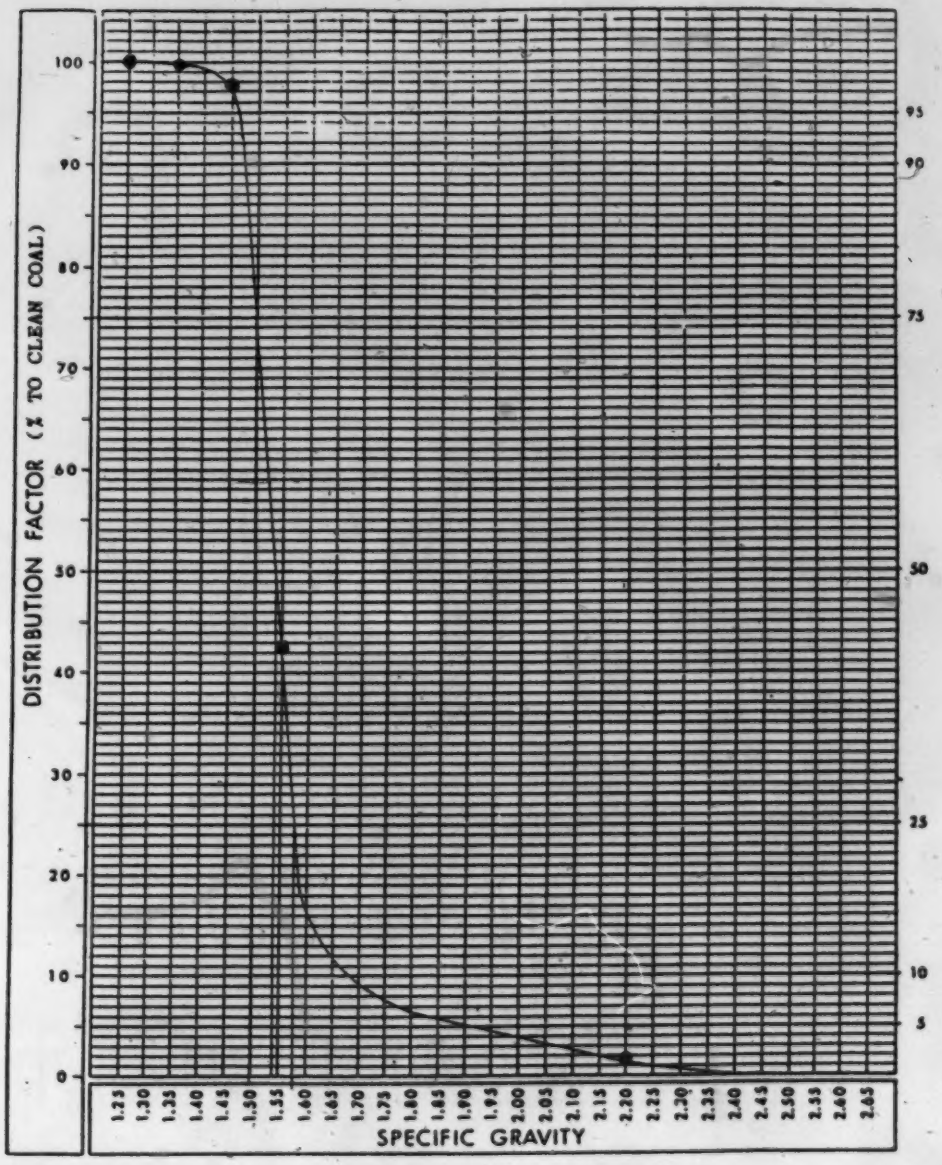



Figure 3.10 Heavy Media Separation Distribution Curve for #9 Seam

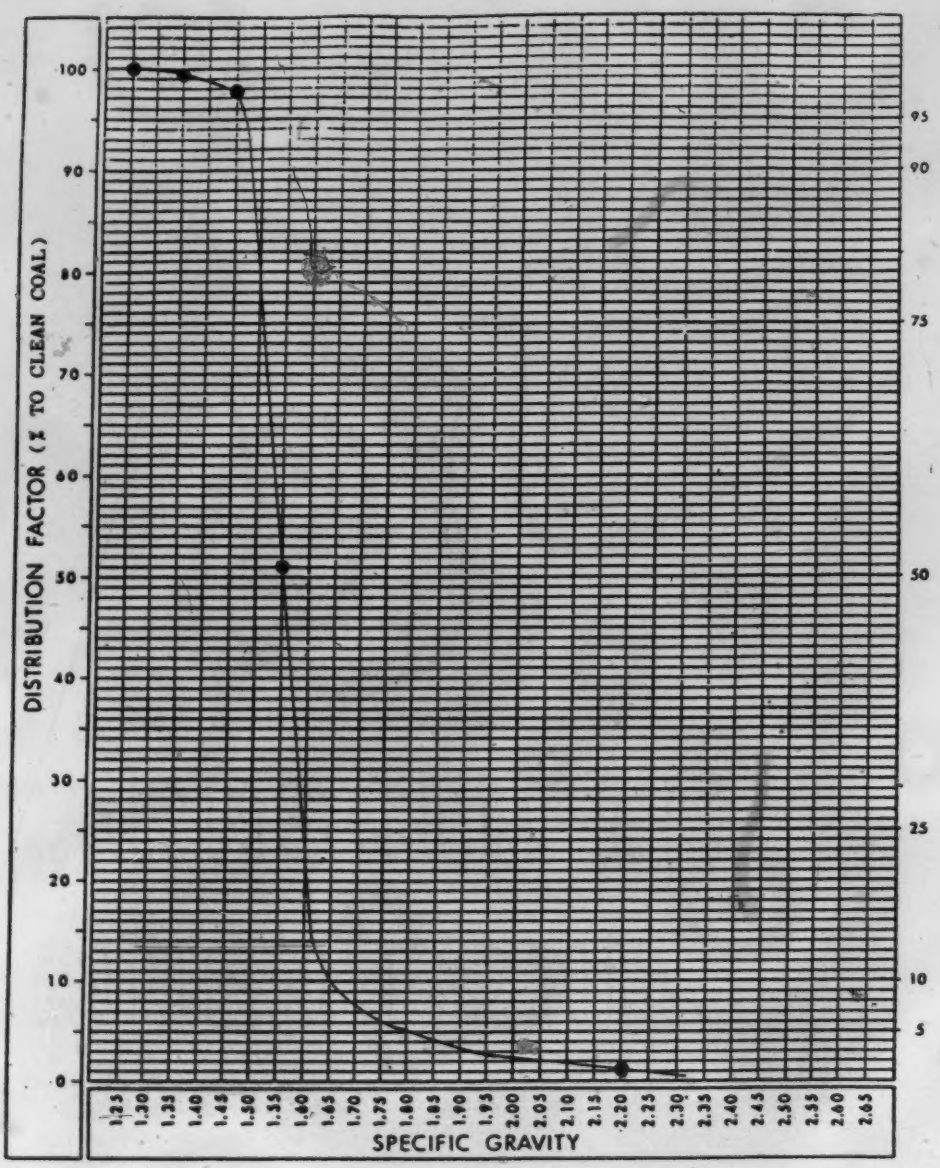



Figure 3.11 Heavy Media Separation Distribution Curve for #10B Seam

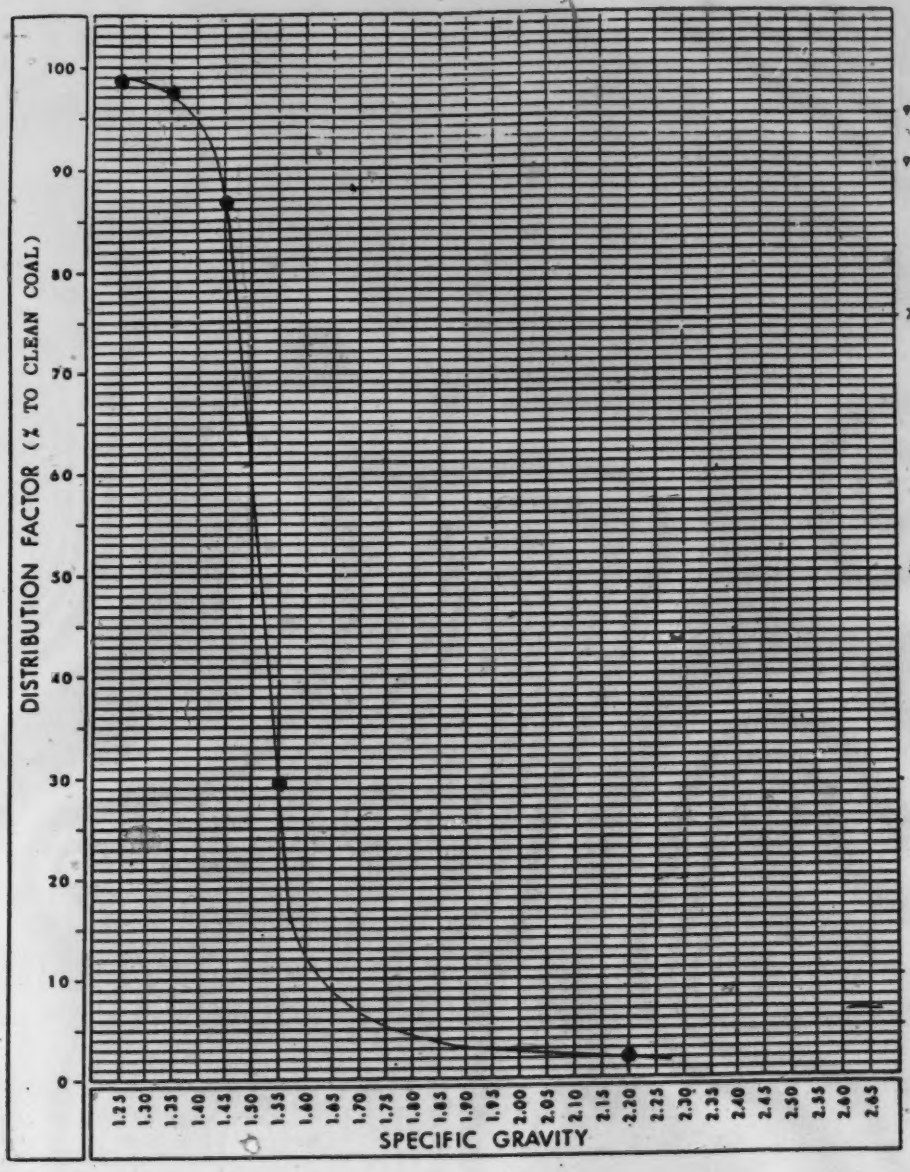



Figure 3.12 Heavy Media Separation Distribution Curve for #10A Seam

cannot be cleaned to the required ash level. The tail on the distribution curve is more clearly shown on the combined generalized curve constructed from the generalized data from all the seams (refer to Figure 2.2).

### 3.5 RELIABILITY OF HEAVY MEDIA YIELD RESULTS

The Monte Carlo technique is used to simulate 100 repetitions of a heavy media cyclone sampling experiment to:

1) obtain a measure of the standard deviation of the calculated yield results,
2) obtain some insight into the impact of sampling error on the calculations.

This approach was necessitated because, for practical reasons, replicate sampling experiments could not be completed. Based on a knowledge of typical sample preparation and analysis errors it was assumed that all sampling increments had a relative error (coefficient of variation) in ash content of 5%. Sampling errors are further assumed to be normally distributed. To account for the composite nature of the samples the increment ash standard deviation was corrected for the number of increments in the sample (i.e. $\sigma_{composite}=\sigma/\sqrt{n}$). The computer program source code is given in Appendix 2 and the results are summarised in Table 3.1.

The yield results for the different seams vary over a relatively narrow range. The estimates of the standard deviation will be used later to estimate the highest level

Table 3.1 Results of the Monte Carlo Simulation

| Seam # | Mean Yield (%) | Standard Deviation (%) | 95% Conf. Interval |
|---|---|---|---|
| 7 | 41.77 | 1.58 | 38.67-44.87 |
| 8 | 65.62 | 1.28 | 63.11-68.13 |
| 9 | 72.64 | 1.07 | 70.54-74.74 |
| 10B | 62.65 | 1.37 | 59.96-65.34 |
| 10A | 66.49 | 1.47 | 63.61-69.37 |

of predictive accuracy that can reasonably be expected from the plant simulator.

# 4. MODEL DEVELOPMENT

## 4.1 OBJECTIVES

The objectives of this study can be summarized as:

1) To develop a mathematical simulator of the plant that can estimate plant yield for different seam blends at different raw coal and clean coal ash levels.
2) To incorporate the valid simulator into a feed blending optimization program which maximizes yield, given seam availabilities and the raw ash content of each seam, subject to all quality and production constraints.

Typically existing simulations of coal preparation plants require as part of their input, detailed washability data of the coal or coals processed. This data is operated on by the distribution curve for each process model within the simulator, in the manner covered in Table 2.1, to arrive at an overall yield and clean coal ash value. However, if the raw coal ash content of a given coal changes the corresponding new washability data must be generated from laboratory testing before the expected material balances can be calculated. In a blend of several seams where ash levels are continually changing it is virtually impossible to know the coal washability. This simulation relates the washability of a given seam to the raw coal ash content, and further assuming linearity, allows the rapid prediction of yield at a specified clean coal ash for a given feed blend.

## 4.2 MODELLING OF THE HEAVY MEDIA CYCLONE CIRCUIT

An extensive search was carried out for mathematical relations which could describe the yield-ash washability curve of a given seam for different levels of raw coal ash. Plitt and Flintoff (53) have used a modified power law for this purpose:

$$Y = \left[ \frac{A_0 - A_i}{A_r - A_i} \right]^{\alpha} \qquad \ldots(4.1)$$

where: $Y$ = yield at cumulative ash $A_0$
$A_0$ = cumulative clean coal ash
$A_i$ = inherent ash (taken to be 2% in this study)
$A_r$ = raw coal ash
$\alpha$ = distribution modulus

The distribution modulus, $\alpha$, can vary from a very small value, e.g. 0.1, for easy to wash coals to 1.0 (or even larger as is the case with seam #10A) for hard to wash coals. This point is illustrated in Figure 4.1 (53).

For a given coal, $\alpha$ is not constant but decreases as $A_0$ increases (refer to Appendix 3). The relationship can be expressed quite adequately, over the range of interest, by one of the following equations:

$$\alpha = A + BA_0 \qquad \ldots(4.2)$$

$$\alpha = A + B\ln(A_0) \qquad \ldots(4.3)$$

where: A and B are constants

Seams #7, #8, #9 and #10A can best be described by equation

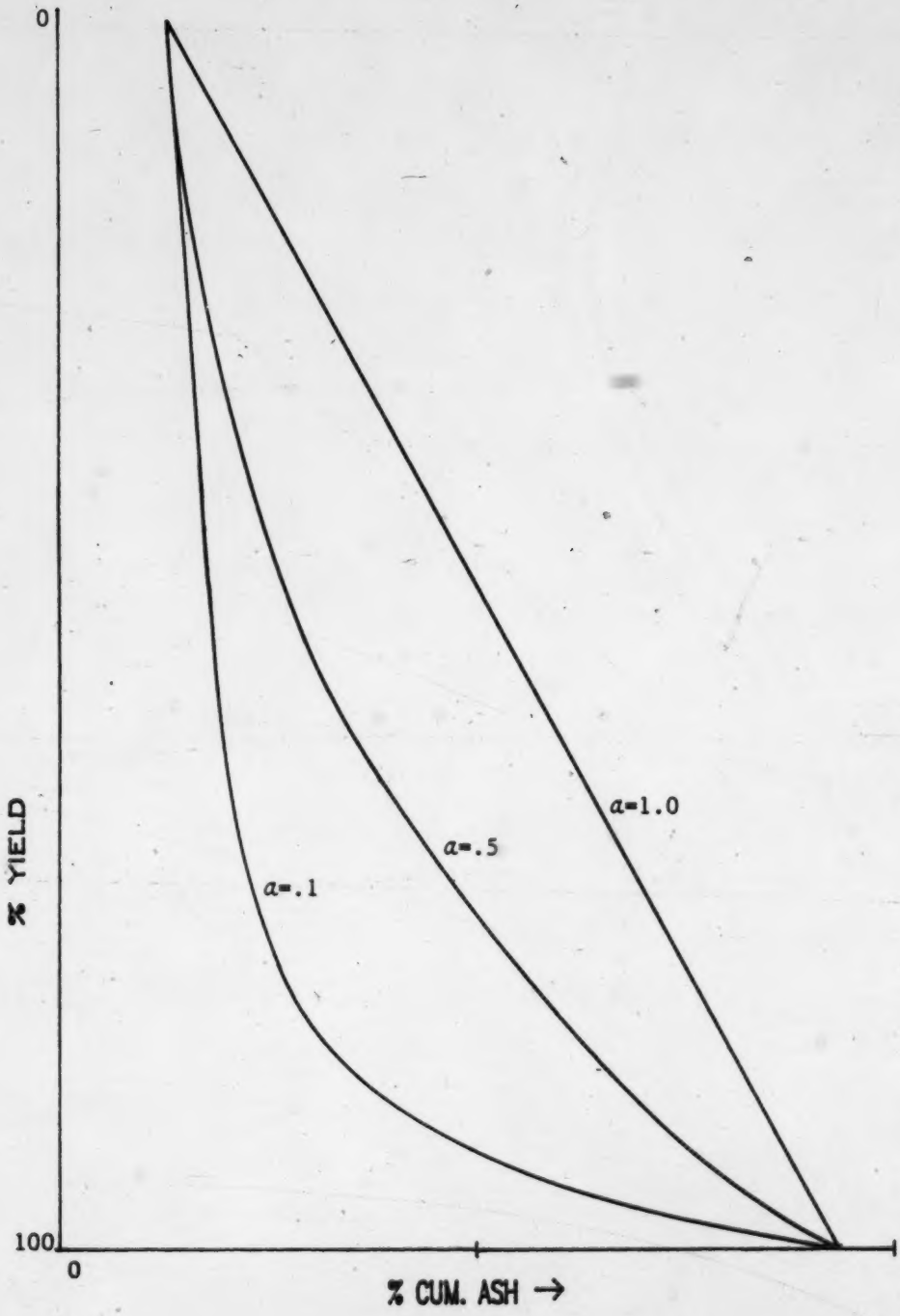



Figure 4.1 Variation in the Distribution Modulus in Yield-Ash Curves

4.3 while seam #10B is best fit by equation 4.2.

Figure 4.2 illustrates how well equations 4.1 and 4.3 represent the yield-ash curve for #8 seam. In the range of interest (clean coal ash values from 8% to 10%) the actual washability points lie almost directly on the model predicted curve. The remaining points, which are outside of the region of interest, lie very close to the model predictions.

For a given coal $\alpha$ also increases as $A_r$ increases (refer to Appendix 4). The relationship for all seams is best described by the following linear equation,

$$\alpha = C + DA_r \qquad \ldots(4.4)$$

where: C and D are constants

Appendices 3 and 4 give the detailed derivation of the above (equations 4.4 and 4.2 or 4.3) for each seam.

A series of plots of $\alpha$ against $A_r$ at different values of $A_0$ (refer to Figure 4.3) shows that the slope of the lines are practically identical. It must be noted that the intercepts decrease as $A_0$ increases which is consistent with the previously stated relation between $\alpha$ and $A_0$. Similar relations and trends exist for the other seams, and are given in Appendix 4. Therefore, it should be possible to express $\alpha$ as follows:

$$\alpha = A + BA_0 + (D(A_r - A_{rb})) \qquad \ldots(4.5)$$

$$\alpha = A + B\ln(A_0) + (D(A_r - A_{rb}))$$

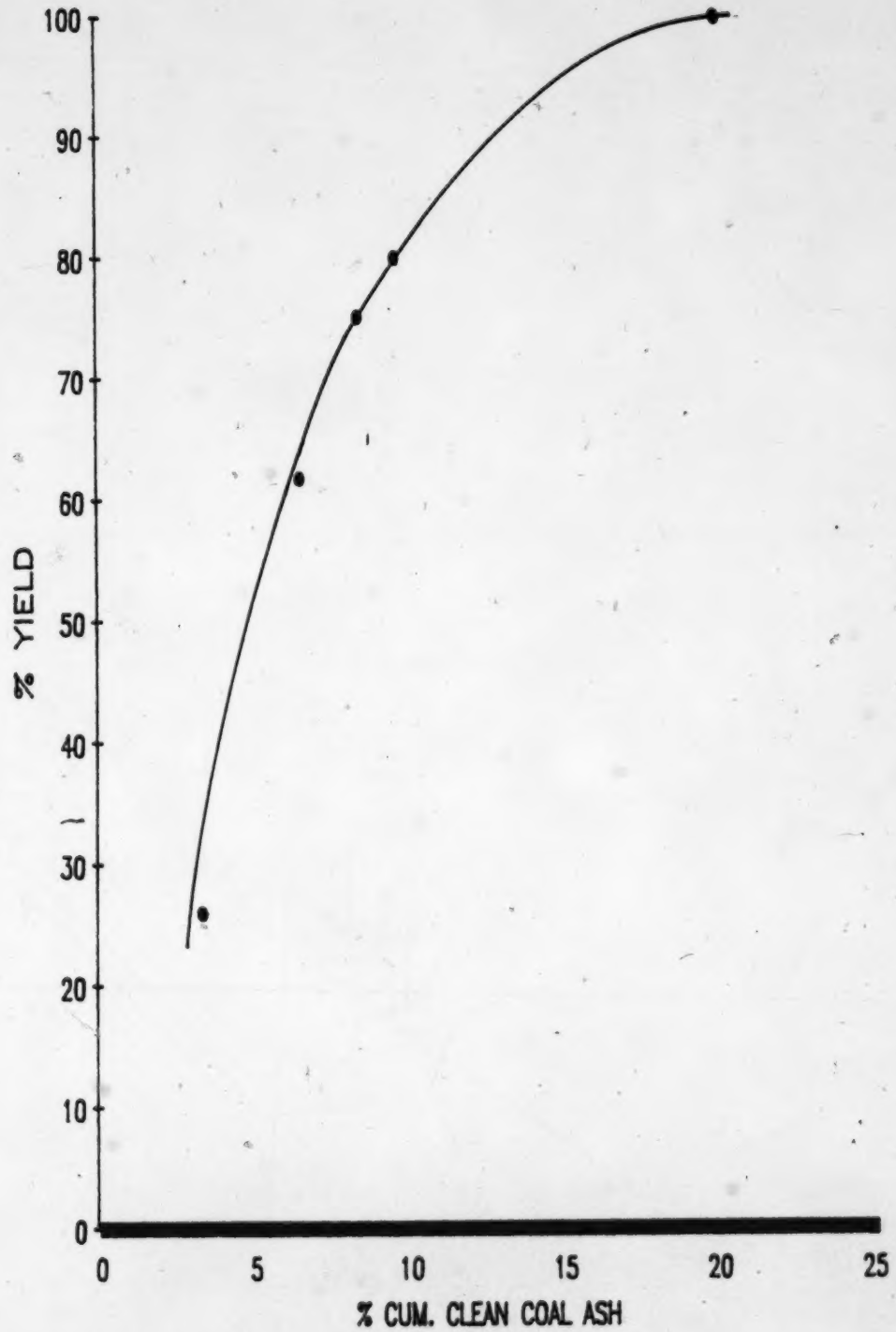



Figure 4.2 Modelling the Washability Data for #8 Seam

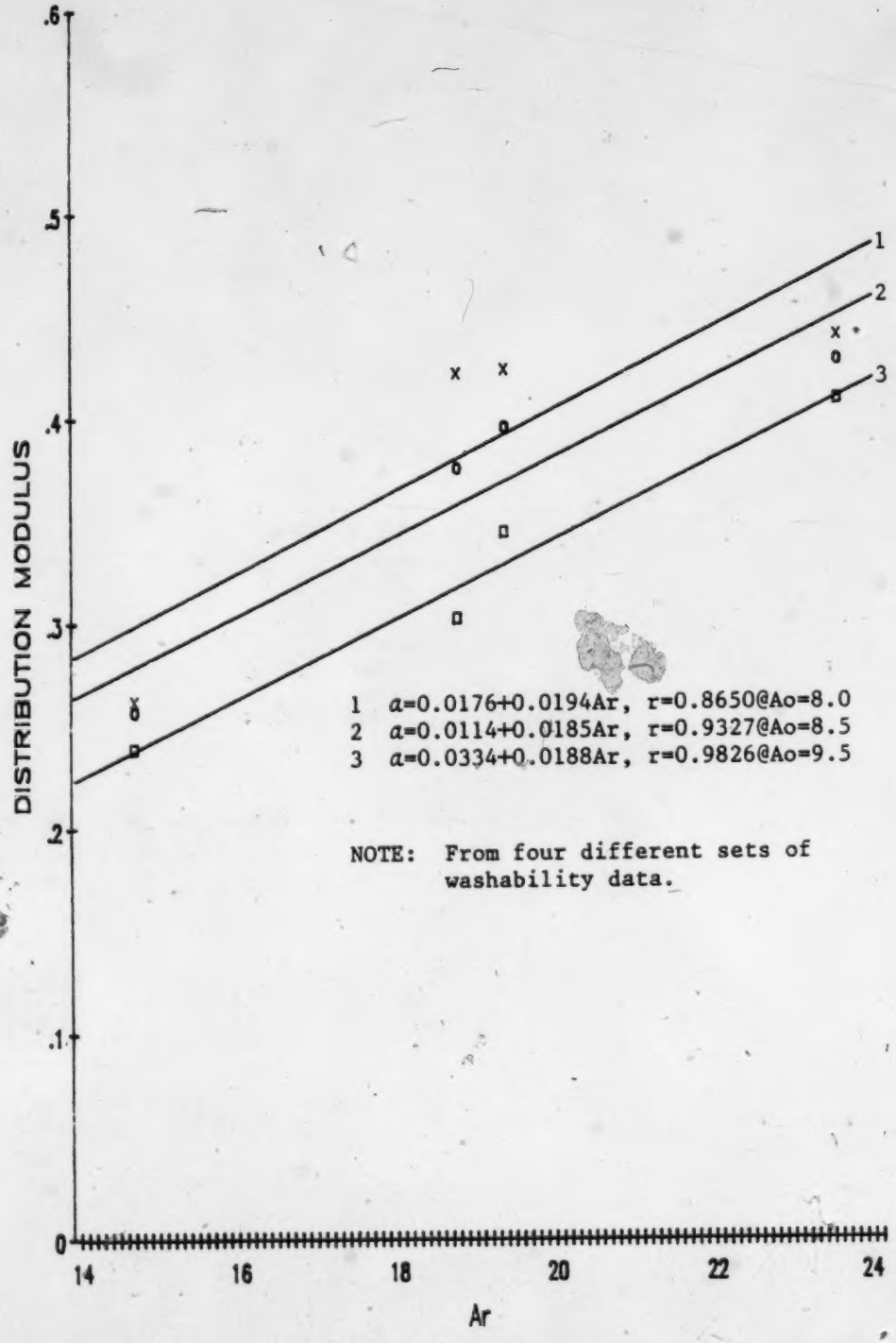



Figure 4.3 Distribution Modulus as a Function of $A_r$ at Different Values of $A_0$ for #8 Seam

where: A and B are previously described constants
D = slope of the $\alpha$ vs. $A_r$ curve
$A_{rb}$ = raw coal ash of the "base case" washability data for that seam (the base case washability is the washability of the reconstituted feed obtained from the plant trials and given in Appendix 5)

Thus, it is possible to determine the value of $\alpha$ at different points along the yield-ash curve, for different values of $A_r$. Once this is known the yield-ash curve, over the range of interest, can be described for a perfect washer by using equation 4.1.

From the individual distribution curves the cutpoint, $d_{50}$, for each seam through the heavy media cyclone circuit can be determined. This permits the calculation of the amount of near gravity material for each seam , at that $d_{50}$, from the base case washability data.

If the amount of near gravity materials for each seam, at its specific $d_{50}$, is plotted against recovery efficiency (using the base case washabilities) the relationship is clear and is given in Figure 4.4. It can be described by the following equation derived by trial and error:

$$R.E. = e^{-0.0002(N.G.)} - 0.1\left[\frac{N.G.}{45}\right]^2 \qquad ...(4.6)$$

where: R. E. = recovery efficiency
N.G. = amount of near gravity material, in percent

It can be seen that the resulting curve fits the data well. This agrees with the shape of the curve given by Walters and Ramani (18) which shows the relationship, for a

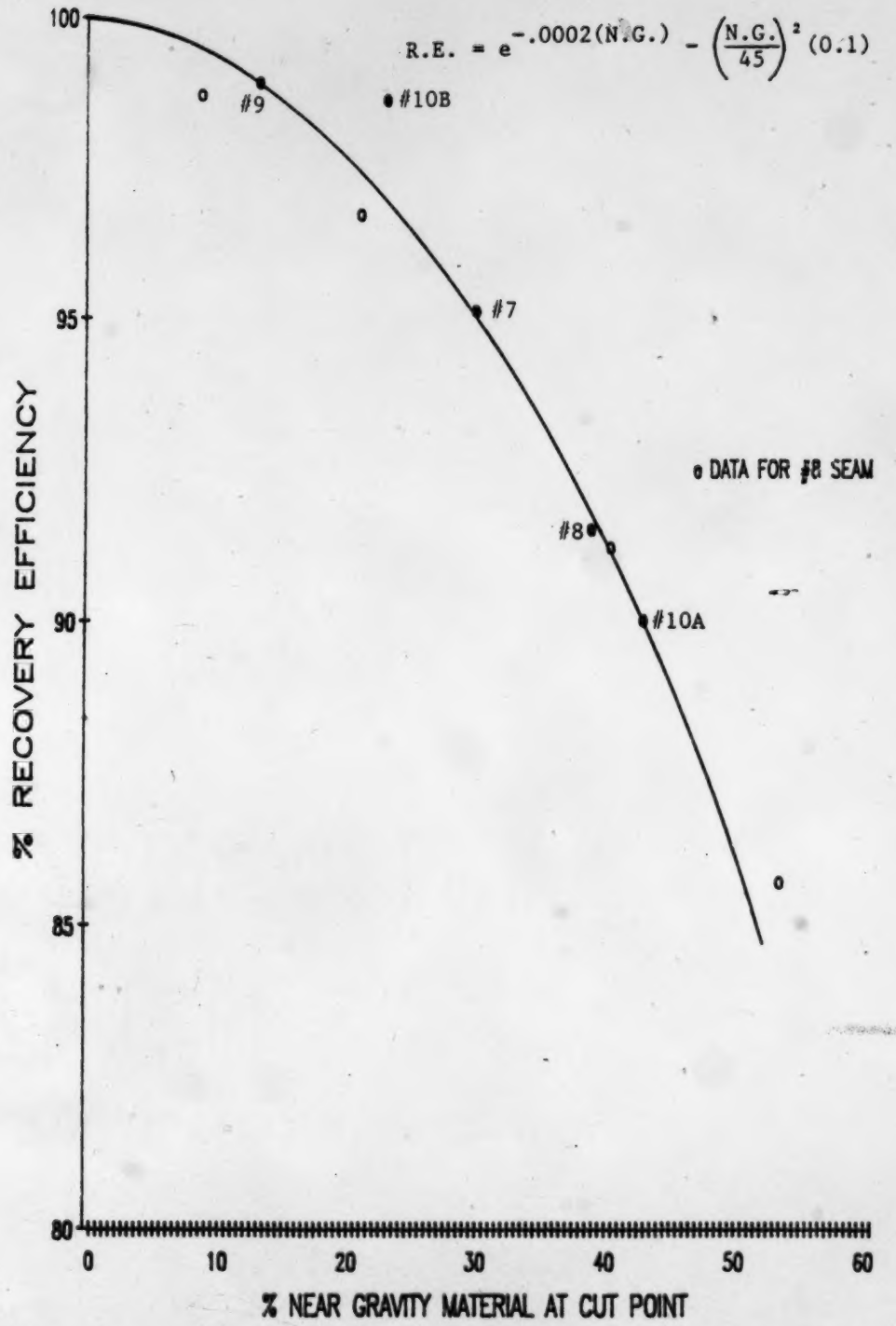



Figure 4.4 Recovery Efficiency as a Function of Near Gravity Material

given coal, between recovery efficiency and $d_{50}$.

The five different seams can thus be tied together by one common principle:

*For a given coal washing unit, operating under a given set of conditions, recovery efficiency is determined by the amount of near gravity material present at the $d_{50}$.*

In other words, if each seam is washed (at different $d_{50}$) such that they all exhibit the same amount of near gravity material then all will have the same value of recovery efficiency.

The next step is to describe the relationship between N.G. and $d_{50}$, for each seam, using the base case washabilities. The equation adopted is given by,

$$N.G. = Ae^{-Bd_{50}} \qquad ...(4.7)$$

where: A,B = empirical constants with
A = (#7 - 14,126), (#8 - 28,240,885), (#9 - 3,114,671), (#10B - 8,012,589) and (#10A - 1,589,736)
B = (#7 - 4.11), (#8 - 9.41), (#9 - 12.56), (#10B - 8.31) and (#10A - 7.05)

The curve plotted in Figure 4.4 fits the recovery efficiency - near gravity relationship for a given seam quite well. This is illustrated by the proximity of the #8 seam data to the model curve. (Recovery efficiency values are determined from the actual yields calculated in section 12.1 and the theoretical yields from the washability curves in appendix 5. The amount of near gravity material is calculated with

the equation above at the cutpoints given in section 12.1.)

The last step is to determine, for each seam and over the clean coal ash range of interest, the correlation between $A_0$ and $d_{50}$. The correlations are linear for all the seams and are given in Figure 4.5.

In each case clean coal ash results are calculated by the method presented in Section 2.2.2. Detailed calculations for #8 seam are given in Appendix 6. The validity of this approach is supported by Crowden and Smith (46) who utilize the slope of the ash-specific gravity curve in their automated specific gravity control strategy. Firth et. al. (27) give the relationship between $d_{50}$ and clean coal ash for different blends and different washing processes, and Shea and Sehgal (54) make use of a similar correlation between sulfur and specific gravity in their quality control strategy.

Thus, for a given seam, yield and clean coal ash through the heavy media cyclones can be determined as follows:

1) Specify a $d_{50}$ and determine the amount of near gravity material and $A_0$
2) Determine the recovery efficiency at the determined amount of near gravity material.
3) Determine $\alpha$ at the the given value of $A_r$.
4) Determine theoretical yield from equation 4.1.
5) Determine actual yield from:

$$Y \text{ (actual)} = Y \text{ (theoretical)} \times R.E.$$

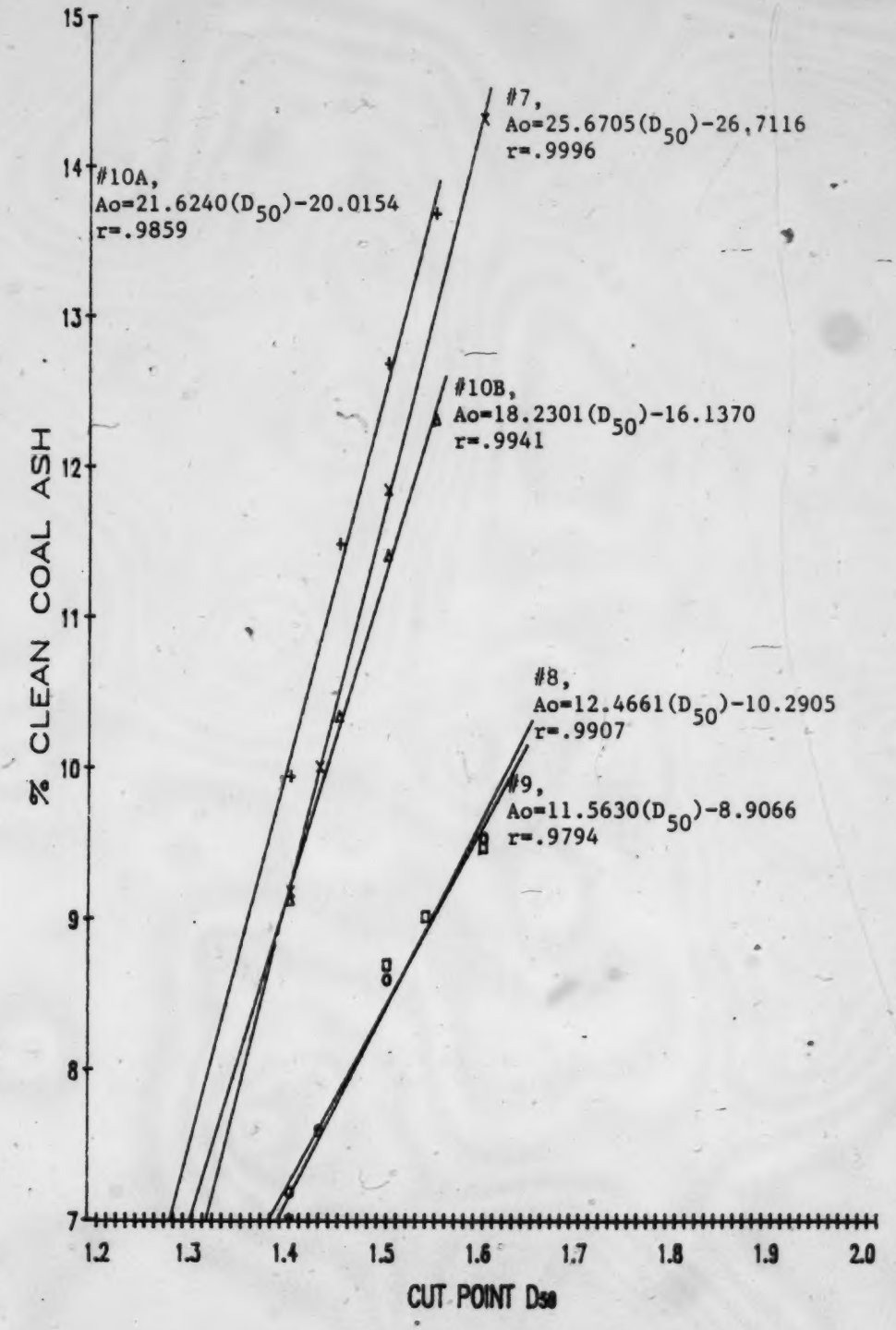



Figure 4.5 Clean Coal Ash vs. Cut Point ($d_{50}$)

For a number of seams the overall yield and $A_0$ is calculated from the weighted average of the seams present in the feed. The actual calculations are carried out by the FORTRAN programs given in Appendix 7. If the proportion of seams in the feed and the $A_r$ of each seam is known the program can determine yields and clean coal ash levels for a range of $d_{50}$ values. Based on previous operating data, the heavy media cyclone feed ash is taken to be 1.7% higher than the total feed ash.

## 4.3 THE FINES CIRCUIT

At the present time a practical way of controlling yield and quality through the water-only cyclones does not exist. Results are mainly determined by the feed blend. Flotation, on the other hand, is always operated at maximum yield conditions because:

1) flotation product ash levels from all seams are within specified levels,
2) the product ash - reagent addition relation is not well defined.

Therefore, in the plant simulator each seam is assigned a typical overall yield and product ash through the fines circuits, based on the results of each plant trial. This approach is supported by almost three years of operating experience which is in general agreement with the typical values arrived at in the plant trials.

The split between the plus and minus 0.5 mm fraction for each seam is determined from the plant trials, through the data smoothing technique shown in Figure 4.6 and is maintained constant. Again, previous operating data indicates that this is a reasonable assumption.

## 4.4 THE PLANT SIMULATOR

### 4.4.1 THE FEED OPTIMIZATION PROGRAM

As previously stated four 5000-tonne capacity silos are available for the storage of raw coal. As a rule, only one seam is mined during a given shift making it possible to store a specific seam in a specific silo. At Line Creek it is operating practice to store only one seam in each silo, whenever possible. A manual cut of the raw coal conveyor is taken every hour and sampled for ash, moisture and F.S.I. Thus the contents of each silo is known with respect to seam and quality. Since the silo feed and silo reclaim conveyors are equipped with scales, the quantity in each silo is also known (quantities are regularly confirmed by manual silo level measurements). This is the information needed for the feed optimization program.

Coal is a composite of material ranging from a specific gravity of about 1.2 (containing mainly organic matter) to over 2.2 (containing mainly mineral matter). The gradation between the two extremes tends to be different for each coal. It is this difference that the feed optimization

NOTES: 1. Original values of % of feed reporting to H.M. were calculated via the two product formula using size analyses data.

2. Corrected values of % of feed reporting to H.M. are given below:

| SEAM # | % +28 MESH | % TO H.M. |
|---|---|---|
| 7 | 77.78 | 74.66 |
| 8 | 82.46 | 80.22 |
| 9 | 83.88 | 81.91 |
| 10B | 82.22 | 79.94 |
| 10A | 77.37 | 74.17 |

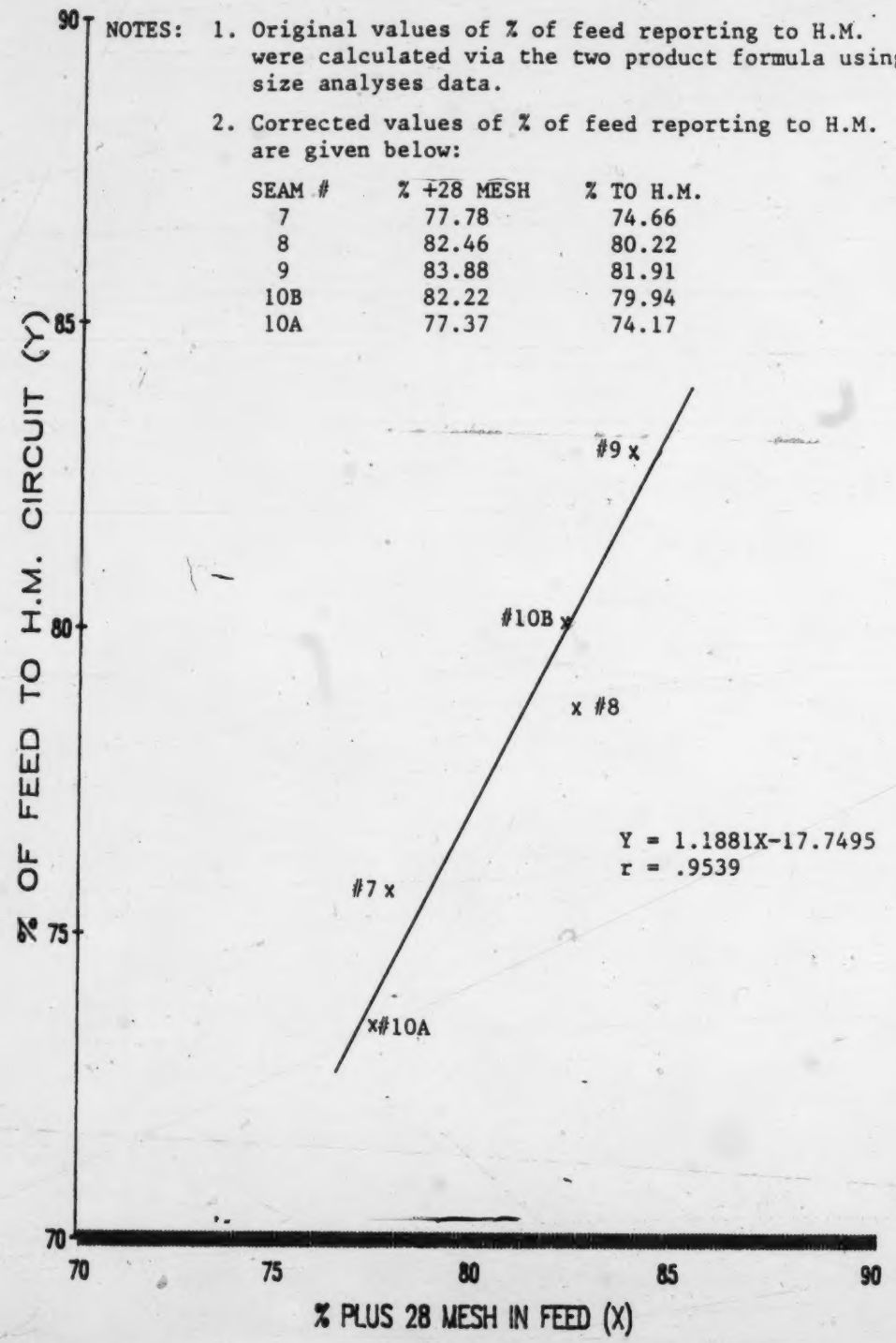



Figure 4.6 Fraction of Feed to Heavy Media Circuit vs. Fraction of Plus 28 Mesh in Feed

program seeks to exploit. Briefly stated; for a given supply of seams at given raw coal ash levels, there is one specific blend (out of many possible) that will provide the required clean coal ash and satisfy all constraints, at the highest possible yield.

This point is illustrated by the following example where the same quantity of coal is processed in two different ways, using the plant simulator described in the previous section, for a target ash between 9.40% and 9.50%. A total of 4000 tonnes is processed each shift over a three shift period.

Given the following raw coal supply and ash levels:

| | | #8 Seam | #9 Seam | #10B Seam | #10A Seam |
|---|---|---|---|---|---|
| Shift #1: | (tonnes) | 4000 | | 4000 | 2000 |
| | (ash) | 20.0 | | 25.0 | 25.0 |

Shift #2: 2000 tonnes of seam #9 is received at 22% ash.

Shift #3: No additional raw coal is received.

Case 1) plant feed is blended at the discretion of the operator. Some of the coal with the better washing characteristics is always left for the next shift so that poorer washing coals can be cleaned to the required level.

Case 2) plant feed is blended at the discretion of the operator, but based on the "ten best" combinations recommended by the feed optimization program. From the recommended blends a choice is made in view of: prevailing operating conditions, present coal supply and anticipated coal supply.

The results of Case 1) are presented in Table 4.1. The results of Case 2) are presented in Table 4.2. The underlined combinations are chosen so as to maximize the use of the poorer washing seam, #10A. Note that in shift #2 number 8 seam is not used because it is wise to maintain a good supply of easily washed coal for the following shift, and it is cumbersome (more chances for error) to maintain a blend from four silos.

The difference between Cases 1 and 2 is a yield increase of 2.52%. For a plant producing 2,000,000 tonnes of clean coal annually, at a typical yield of 66%, this represents an additional output of 76,363 tonnes. At a positive cash flow of $40 (subtracting drying, shipping and port costs) the additional annual cash flow is over three million dollars. (Processing costs are not substantially increased.)

**4.4.2 PROGRAM CONSTRAINTS**

The recommended blends must satisfy the following constaints:

1) Clean coal ash must fall within an acceptable range which is defined by the programmer. If the range is too narrow, some optimal blends may be excluded (this point will be covered in the following section). If too wide, an element of inconsistency will be introduced. In this program the acceptable range is 9.40 to 9.50% ash (this can be changed by simply changing one line in the

Table 4.1 Operator Selected Blends and Product Specifications

| | Proportion of Seams Processed(%) #8 | #9 | #10B | #10A | Clean Coal Ash (%) | Plant Yield (%) |
|---|---|---|---|---|---|---|
| Shift #1 | 75 | - | 25 | - | 9.47 | 75.77 |
| Shift #2 | 25 | 25 | 50 | - | 9.43 | 67.37 |
| Shift #3 | - | 25 | 25 | 50 | 9.42 | 43.04 |
| | | | | Overall | 9.444 | 62.06 |

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# Table 4.2 Optimized Blends and Product Specifications

Shift #1: Optimization Program I/O

RAW COAL ASH
SEAM: #7 #8 #9 #10B #10A
0.0,20.0,0.0,25.0,25.0
TONNES OF: #7 #8 #9 #10B #10A
0,4000,0,4000,2000

| #7 | #8 | #9 | #10B | #10A | SG | CC% | HM% | YLD% | RE |
|---|---|---|---|---|---|---|---|---|---|
| .00 | 50.00 | .00 | 45.00 | 5.00 | 1.48 | 9.48 | 64.49 | 67.73 | .94 |
| .00 | 47.50 | .00 | 47.50 | 5.00 | 1.47 | 9.41 | 62.88 | 66.25 | .93 |
| .00 | 50.00 | .00 | 40.00 | 10.00 | 1.47 | 9.40 | 62.48 | 66.00 | .93 |
| .00 | 47.50 | .00 | 45.00 | 7.50 | 1.47 | 9.44 | 62.61 | 65.99 | .93 |
| .00 | 45.00 | .00 | 50.00 | 5.00 | 1.47 | 9.48 | 62.73 | 65.99 | .93 |
| .00 | 50.00 | .00 | 37.50 | 12.50 | 1.47 | 9.42 | 62.21 | 65.75 | .93 |
| .00 | 47.50 | .00 | 42.50 | 10.00 | 1.47 | 9.46 | 62.34 | 65.74 | .93 |
| .00 | 45.00 | .00 | 47.50 | 7.50 | 1.47 | 9.50 | 62.47 | 65.73 | .93 |
| .00 | 50.00 | .00 | 35.00 | 15.00 | 1.47 | 9.45 | 61.94 | 65.49 | .93 |
| .00 | 47.50 | .00 | 40.00 | 12.50 | 1.47 | 9.48 | 62.07 | 65.49 | .93 |

Shift #2: Optimization Program I/O

RAW COAL ASH
SEAM: #7 #8 #9 #10B #10A
0.0,0.0,22.0,25.0,25.0
TONNE OF: #7 #8 #9 #10B #10A
0,0,2000,2600,1400

| #7 | #8 | #9 | #10B | #10A | SG | CC% | HM% | YLD% | RE |
|---|---|---|---|---|---|---|---|---|---|
| .00 | .00 | 50.00 | 45.00 | 5.00 | 1.48 | 9.47 | 66.20 | 66.05 | .94 |
| .00 | .00 | 50.00 | 42.50 | 7.50 | 1.48 | 9.49 | 65.95 | 65.81 | .94 |
| .00 | .00 | 47.50 | 47.50 | 5.00 | 1.47 | 9.40 | 64.46 | 64.62 | .93 |
| .00 | .00 | 45.00 | 50.00 | 5.00 | 1.47 | 9.47 | 64.24 | 64.44 | .93 |
| .00 | .00 | 47.50 | 45.00 | 7.50 | 1.47 | 9.43 | 64.19 | 64.36 | .93 |
| .00 | .00 | 45.00 | 47.50 | 7.50 | 1.47 | 9.49 | 63.97 | 64.19 | .93 |
| .00 | .00 | 47.50 | 42.50 | 10.00 | 1.47 | 9.45 | 63.92 | 64.11 | .93 |
| .00 | .00 | 50.00 | 37.50 | 12.50 | 1.47 | 9.41 | 63.88 | 64.03 | .93 |
| .00 | .00 | 47.50 | 40.00 | 12.50 | 1.47 | 9.47 | 63.65 | 63.86 | .93 |
| .00 | .00 | 50.00 | 35.00 | 15.00 | 1.47 | 9.44 | 63.61 | 63.78 | .93 |

Shift #3: No optimization takes place. The remaining coal is processed to achieve the required clean coal ash.

| | Proportion of Seams Processed (%) | | | | Clean Coal Ash (%) | Plant Yield (%) |
|---|---|---|---|---|---|---|
| | #8 | #9 | #10B | #10A | | |
| Shift #3 | 50 | - | 30 | 20 | 9.44 | 64.46 |
| | | | | Overall | 9.443 | 64.58 |

program).

2) Blends must be consistent with the long term supply of each seam, while allowing enough flexibility for optimization to take place. "Good" seams must not be over used and "poor" seams must not be excluded. The acceptable proportions of the seams are:

**#7 seam**

a) Minimum; 15% if amount available is greater than 15%, or the amount available is less than 15%.

b) Maximum; 50%.

**#8 seam**

a) Minimum; 0%.

b) Maximum; 50%.

**#9 seam**

a) Minimum; 0%.

b) Maximum; 50%.

**#8 seam + #9 seam**

a) Minimum; 0%.

b) Maximum; 65%.

**#10B seam**

a) Minimum; 0%.

b) Maximum; 50%.

**#10A seam**

a) Minimum; 5% if amount available is greater than 5%, or the amount available if less than 5%.

b) Maximum; 50%.

3) Clean coal F.S.I. results must be between 5.5 and 6.5

inclusive. F.S.I. is to a large degree inherent to each seam., Typical values are:

| SEAM | F.S.I. |
|---|---|
| #7 | 6.5 → 7.5 |
| #8 | 4.5 → 5 |
| #9 | 5 → 6 |
| #10B | 6.5 → 7.5 |
| #10A | 6.5 → 7.5 |

If acceptable blends are maintained F.S.I. results will fall within the required range most of the time. However, F.S.I. cannot always be estimated by averaging and results are somewhat subjective.

4) 4000 tonnes of raw coal must be available for processing for one 12-hour shift.

The yield of a given seam can be mathematically described as,

$$Y_i = f(W_i , A_{0i}) \qquad ...(4.8)$$

where: $Y_i$; i=1,2,3,4,5 = the yield of a given seam with overall washability $W_i$, as described in section 2.6, cleaned to some ash level $A_{0i}$

Therefore, the overall yield of a given feed blend is,

$$Y_T = \frac{\sum_{i=1}^{5} M_i Y_i}{\sum_{i=1}^{5} M_i} \qquad ...(4.9)$$

where: $Y_T$ = overall plant yield

$M_i$ = amount of each seam in the feed.

The overall plant product ash is,

$$A_{0T} = \frac{\sum_{i=1}^{5} M_i Y_i A_{0i}}{\sum_{i=1}^{5} M_i Y_i} \qquad \ldots(4.10)$$

where: $A_{0T}$ = overall product ash

Assuming linearity, the overall product F.S.I can be approximated as,

$$F.S.I._{0T} \approx \frac{\sum_{i=1}^{5} M_i Y_i F.S.I._i}{\sum_{i=1}^{5} M_i Y_i} \qquad \ldots(4.11)$$

where: $F.S.I._{0T}$ = overall product F.S.I. given the average seam values, $F.S.I._i$

Given the above, constraints 1 to 4 can be expressed as follows:

1)

$$9.4\% \leq A_{0T} \leq 9.5\% \qquad \ldots(4.12)$$

2)

$$0.15 \leq \frac{M_i}{\sum_{i=1}^{5} M_i} \leq 0.5 \text{ iff } \frac{M_i(\text{available})}{\sum_{i=1}^{5} M_i} > 0.15 \qquad \ldots(4.13)$$

or

$$\frac{M_1}{\sum_{i=1}^{5} M_i} = \frac{M_1(\text{available})}{\sum_{i=1}^{5} M_i} \text{ iff } \frac{M_1(\text{available})}{\sum_{i=1}^{5} M_i} \leq 0.15$$

$$0 \leq \frac{M_2}{\sum_{i=1}^{5} M_i} \leq 0.5 \qquad \ldots(4.14)$$

$$0 \leq \frac{M_3}{\sum_{i=1}^{5} M_i} \leq 0.5 \qquad \ldots(4.15)$$

$$0 \leq \frac{M_4}{\sum_{i=1}^{5} M_i} \leq 0.5 \qquad \ldots(4.16)$$

$$0.05 \leq \frac{M_5}{\sum_{i=1}^{5} M_i} \leq 0.5 \text{ iff } \frac{M_5(\text{available})}{\sum_{i=1}^{5} M_i} > 0.05 \qquad \ldots(4.17)$$

or

$$\frac{M_5}{\sum_{i=1}^{5} M_i} = \frac{M_5(\text{available})}{\sum_{i=1}^{5} M_i} \text{ iff } \frac{M_5(\text{available})}{\sum_{i=1}^{5} M_i} \leq 0.05$$

where:
$M_i$ (i=1,2,3,4,5) = the amounts of seams #7, #8, #9, #10B and #10A, respectively, in the feed.

3)

$$5.5 \leq \text{F.S.I.}_{OT} \leq 6.5 \qquad \ldots(4.18)$$

4)

$$\sum_{i=1}^{5} M_i = 4000 \text{ tonnes} \qquad \ldots(4.19)$$

The objective is to maximze $Y_T$ while satisfying all constraints. The blending and washing processes are schematically illustrated in Figure 4.7.

**4.4.3 ALGORITHM DEVELOPMENT**

The input to the plant simulator (given in Appendix 7) includes the raw coal ash of each seam to be processed and the seam proportions in the feed. The latter can be entered as a percentage or as actual tonnages. For example,

Raw Coal Ash Entry:
0.0,20.0,0.0,25.0,25.0

Tonnes Of Each Seam:
0.0,50.0,0.0,30.0,20.0

or

Tonnes Of Each Seam
0.0,2000.,0.0,1200.0,800.0

The input stipulates that: there is no #7 seam, #8 seam contains 20.0% ash and makes up 50% of the feed, there is no #9 seam, #10B seam contains 25.0% ash and makes up 30% of the feed, #10A seam contains 25.0% ash and makes up 20% of the feed.

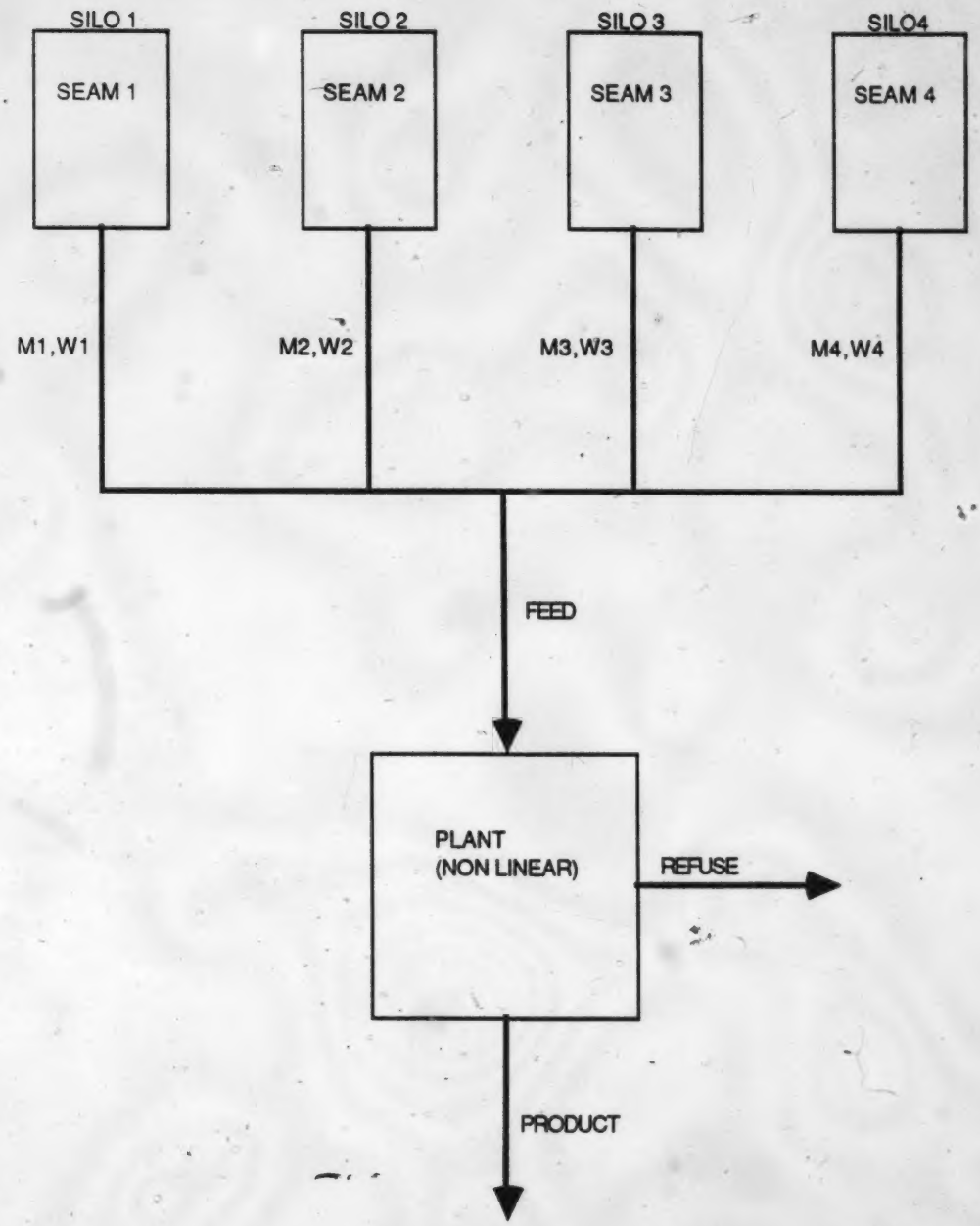



Figure 4.7 Schematic Representation of the Blending and Washing Processes

The program will process the given blend in increments of 0.01 specific gravity units from a cut point of 1.40 to 1.60, through the heavy media circuit. A sorting routine (borrowed from the feed optimization program) is used to list the output in order of plant yield. An example is presented in Table 4.3. The output includes:(i) the proportion of each seam, (ii)the cut point through the heavy media cyclones (SG), (iii) the overall clean coal ash (CC%), (iv) the yield through the heavy media cyclones, (v) the total plant yield (YLD%) (including a factored increase of 1.038 to account for the increase in product moisture), and, (vi) recovery efficiency (RE).

The optimization program (given in Appendix 7) uses the basic plant simulator to derive all yield and quality results. The input is very similar and includes the raw coal ash and tonnage of each available seam. Examples are given in Section 4.4.1.

The optimization algorithm follows the sequence:

1) The acceptable proportions of each seam are defined.
2) Yield and clean coal ash are calculated for each seam, with raw coal ash values other than 0.0, for cut points (through the heavy media cyclones) from 1.40 to 1.55 in increments of 0.01 specific gravity units.
3) At each cut point a group of nested "DO" loops generate all possible seam combinations that satisfy the constraints in increments of 2.5 percentage points. This matches the control possible with the conveyor scales

Table 4.3 Output of the Basic Plant Simulator

| #7 | #8 | #9 | #10B | #10A | S.G. | CC% | H.M.% | YLD % | R.F. |
|---|---|---|---|---|---|---|---|---|---|
| .00 | 50.00 | .00 | 30.00 | 20.00 | 1.60 | 11.22 | 76.48 | 77.21 | .99 |
| .00 | 50.00 | .00 | 30.00 | 20.00 | 1.59 | 11.08 | 75.64 | 76.51 | .99 |
| .00 | 50.00 | .00 | 30.00 | 20.00 | 1.58 | 10.94 | 74.71 | 75.78 | .99 |
| .00 | 50.00 | .00 | 30.00 | 20.00 | 1.57 | 10.81 | 73.77 | 75.02 | .98 |
| .00 | 50.00 | .00 | 30.00 | 20.00 | 1.56 | 10.68 | 72.80 | 74.23 | .98 |
| .00 | 50.00 | .00 | 30.00 | 20.00 | 1.55 | 10.54 | 71.78 | 73.40 | .98 |
| .00 | 50.00 | .00 | 30.00 | 20.00 | 1.54 | 10.41 | 70.71 | 72.54 | .97 |
| .00 | 50.00 | .00 | 30.00 | 20.00 | 1.53 | 10.28 | 69.59 | 71.63 | .97 |
| .00 | 50.00 | .00 | 30.00 | 20.00 | 1.52 | 10.14 | 68.41 | 70.68 | .97 |
| .00 | 50.00 | .00 | 30.00 | 20.00 | 1.51 | 10.01 | 67.17 | 69.67 | .96 |
| .00 | 50.00 | .00 | 30.00 | 20.00 | 1.50 | 9.88 | 65.86 | 68.60 | .95 |
| .00 | 50.00 | .00 | 30.00 | 20.00 | 1.49 | 9.75 | 64.46 | 67.47 | .95 |
| .00 | 50.00 | .00 | 30.00 | 20.00 | 1.48 | 9.62 | 62.98 | 66.27 | .94 |
| .00 | 50.00 | .00 | 30.00 | 20.00 | 1.47 | 9.49 | 61.40 | 64.99 | .93 |
| .00 | 50.00 | .00 | 30.00 | 20.00 | 1.46 | 9.37 | 59.71 | 63.61 | .92 |
| .00 | 50.00 | .00 | 30.00 | 20.00 | 1.45 | 9.24 | 57.89 | 62.13 | .90 |
| .00 | 50.00 | .00 | 30.00 | 20.00 | 1.44 | 9.12 | 55.92 | 60.53 | .88 |
| .00 | 50.00 | .00 | 30.00 | 20.00 | 1.43 | 9.00 | 53.79 | 58.79 | .86 |
| .00 | 50.00 | .00 | 30.00 | 20.00 | 1.42 | 8.88 | 51.47 | 56.90 | .84 |
| .00 | 50.00 | .00 | 30.00 | 20.00 | 1.41 | 8.77 | 48.94 | 54.84 | .81 |
| .00 | 50.00 | .00 | 30.00 | 20.00 | 1.40 | 8.66 | 46.16 | 52.57 | .78 |

without making the computation too cumbersome.

4) Each seam combination is checked to determine if the required 4000 tonnes of raw coal are available.

5) Each seam combination is checked to see if the proportion of seam #8 plus #9 exceeds 65%.

6) The total clean coal ash result is checked to determine if it falls within the required range.

7) If the clean coal ash range is satisfied the total plant yield is calculated.

8) Subroutine sort (a standard Bubble Sort [55]) compares the new yield value against those already held (a maximum of 10). If the value is higher than any of these and if 10 values are already being held then it will be kept in the appropriate position in order of yield. The lowest value previously held will be dropped.

The output (examples are given in Section 4.4.1) includes: the ten best combinations in order of predicted plant yield with corresponding seam proportions, predicted cut point, predicted clean coal ash result, predicted yield through the heavy media cyclones and predicted recovery efficiency through the heavy media cyclones.

The range of cut points (1.40 → 1.55) covers the full range used in the plant. The increments of 0.01 match the finest plant control possible. The programs, kept on a floppy disc, are run on an I.B.M. P.C. The optimization program will provide an output in 20 minutes or less. The actual time depends on tonnages and the number of seams

available. If the blend includes three seams computing time is from one to five minutes. If four seams are used computing time is from 10 to 20 minutes.

The acceptable clean coal ash range must be chosen very carefully. If too narrow some optimal combinations will be excluded. This is because clean coal ash is very sensitive to heavy media cut points. This is illustrated in the previous output example. A balance must be achieved between computation efficiency and identifying optimal combinations. It is not too significant if a small number of optimal combinations are not identified since most of the surrounding optima, with similar seam combinations, will be identified. These tend to have identical recovery efficiency values.

### 4.4.4 VALIDATION OF THE SIMULATOR

To be considered valid the simulator must duplicate the performance of the plant given: (i) the seam proportions processed, (ii) the ash content of each seam and (iii) the overall clean coal ash. Even if it is valid, it is not always clearly identified since the basis of comparison (yield as determined from conveyor scale readings) is by no means error free. The plant feed and product conveyor scales are accurate to within ± 2%, depending on such factors as:

- temperature and temperature fluctuations,
- amount of debris (dust) in area of weigh bridge,
- load profile on the conveyor,

- period of time since the last scale check,
- condition of conveyor belt,
- condition of idlers and pulleys,
- condition of the scale.

Figure 4.8 shows a comparison between plant reported yields and the correponding values as predicted by the simulator. The yield calculated from the empirical formulae given in section 2.6 is also included. The three yield plots follow the same trend, however, it is apparent that the simulator predictions track the plant reported values more closely.

Each reported yield point represents 10,000 tonnes of clean coal or one unit train, as measured by the plant product conveyor scale. The yields calculated by the simulator and by the empirical formulae were obtained using the overall seam blends, raw coal ash values and the overall clean coal ash for each 10,000 tonne increment. The data of Figure 4.8 is given in Table 4.4.

Factors that will introduce differences between the yield estimates include:

a) errors in the estimation of the seam blends,
b) errors in the estimation of the raw coal ash levels,
c) errors in the determination of the clean coal ash levels,
d) variations from the standard product moisture (taken to be 7.8%),
e) error inherent to the models such as,

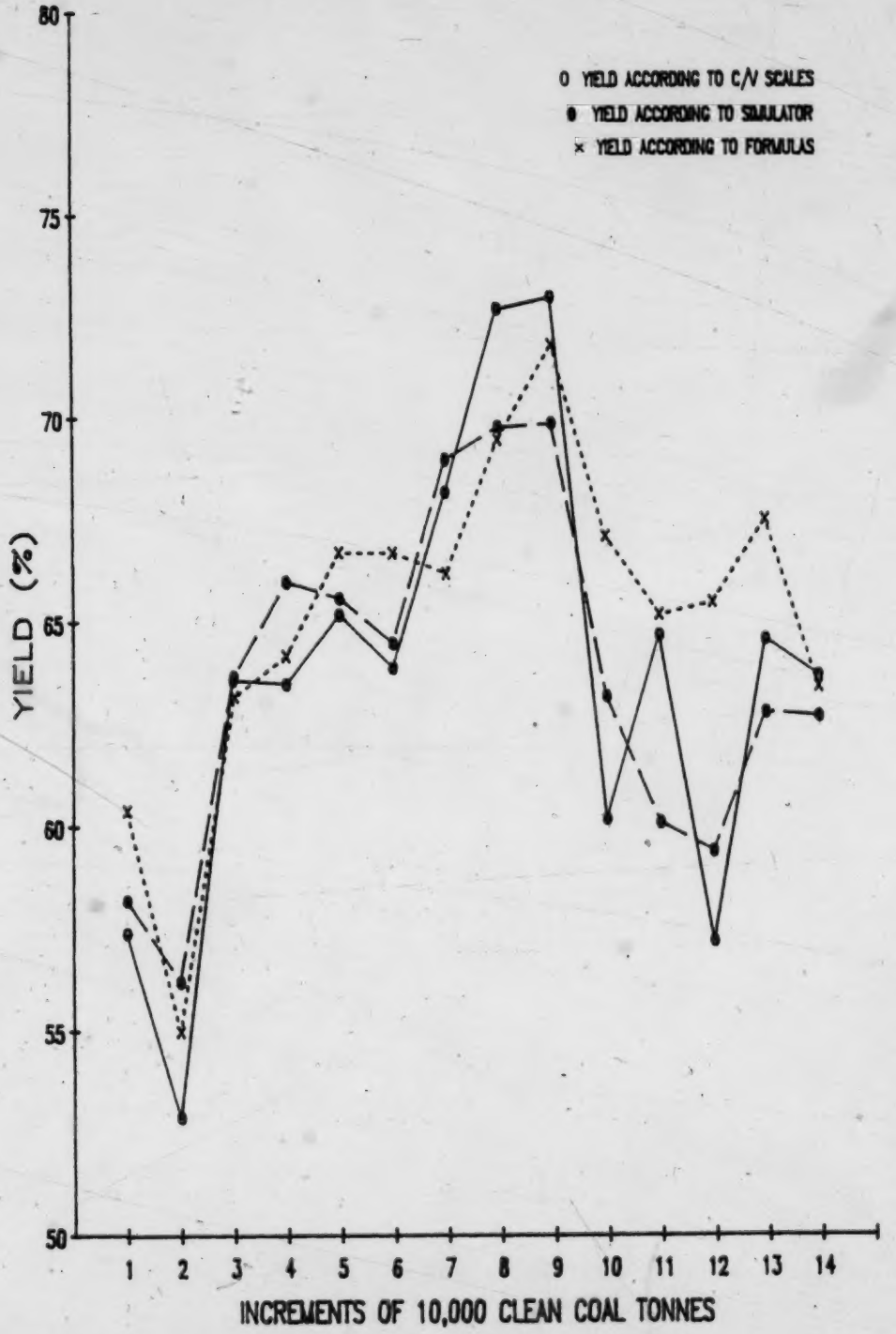



Figure 4.8 Comparison Between Reported and Calculated Plant Yields

Table 4.4 Reported and Calculated Yields

| | RAW COAL (TONNES) | CLEAN COAL (TONNES) | SCALE YIELDS (%) | SIMULATOR YIELDS (%) | FORMULA YIELDS (%) |
|---|---|---|---|---|---|
| 1. | 17,422 | 10,000 | 57.4 | 58.2 | 60.4 |
| 2. | 18,904 | 10,000 | 52.9 | 56.2 | 55.0 |
| 3. | 15,723 | 10,000 | 63.6 | 63.7 | 63.2 |
| 4. | 15,748 | 10,000 | 63.5 | 66.0 | 64.2 |
| 5. | 15,337 | 10,000 | 65.2 | 65.6 | 66.7 |
| 6. | 15,649 | 10,000 | 63.9 | 64.5 | 66.7 |
| 7. | 14,663 | 10,000 | 68.2 | 69.0 | 66.2 |
| 8. | 13,755 | 10,000 | 72.7 | 69.8 | 69.5 |
| 9. | 13,699 | 10,000 | 73.0 | 69.9 | 71.8 |
| 10. | 16,611 | 10,000 | 60.2 | 63.2 | 67.1 |
| 11. | 15,456 | 10,000 | 64.7 | 60.1 | 65.2 |
| 12. | 17,483 | 10,000 | 57.2 | 59.4 | 65.5 |
| 13. | 15,480 | 10,000 | 64.6 | 62.8 | 67.5 |
| 14. | 15,699 | 10,000 | 63.7 | 62.7 | 63.4 |

variations in the amount of -28 mesh material in the feed,

variations in seam washability,

variations in seam behaviour through the water-only cyclones and flotation circuits.

Poor operating practices such as inadequate monitoring of flotation, process interruptions (unscheduled shut downs) and wide fluctuations in instantaneous ash results will cause yield losses and thus introduce differeneces between reported an calculated yields.

To determine the degree of agreement between reported and calculated yields a linear regression of reported yield(s) on calculated yield was performed.

For the yield as calculated from the empirical formulae the resulting model is,

$$Y = 1.14X - 10.63 \qquad ...(4.20)$$

where: Y = reported yield
X = calculated yield

The square of the correlation coefficient is $r^2 = 0.68$ with $r = 0.83$. Thus the model indicates that 68% of the variation in the reported yield can be explained by the calculated yield. (N.B. The *sampling* variance on the reported yield, Y, is quite large relative to the range of yields encountered. This has the effect of limiting $r^2$ to be something less that 1, even if the linear model was perfect.) Although the r value indicates a valid correlation at a confidence level of

99.9%(56), a significant portion of the yield variation is left unexplained.

A similar fit of reported yield on simulator yield gave,

$$Y = 1.2X - 12.74 \qquad ...(4.21)$$

with $r^2 = 0.83$ and $r = 0.91$. These results are obviously much better, as would have been expected from Figure 4.8. The simulator yield can account for 83% of the variation in the reported yield.

For a linear model of the form,

$$Y = b_0 + b_1X \qquad ...(4.22)$$

where: $b_0$ = the intercept
$b_1$ = the slope

one can compute confidence levels for the estimated parameters. For the latter linear correlation these values, corresponding to the 95% confidence level, are presented in Table 4.5. The confidence interval for $b_0$ allows for the possibility that the true intercept is 0. Moreover, the confidence interval on $b_1$ allows for the possibility that the true slope is 1.0. These would be the expected results if the simulator was both unbiased and reasonably accurate.

Turning to the limiting value of $r^2$, Draper and Smith(57) observe that the residual mean square, $s^2$, is an estimate of $\sigma^2$, the sampling variance on the dependent variable. Given an estimate of $\sigma$, based on typical standard

Table 4.5 Confidence Intervals For Model Coefficients

| COEFFICIENT | ESTIMATE | STANDARD ERROR | CONFIDENCE INTERVAL |
|---|---|---|---|
| $B_0$ | -12.7362 | 9.8601 | 21.4852 |
| $B_1$ | 1.1998 | 0.1546 | 0.3369 |

Therefore, the 95% confidence intervals for the coefficients are:

$$-34.2214 \leq B_0 \leq 8.7490$$

$$0.8629 \leq B_1 \leq 1.5367$$

deviations of heavy media circuit yields as determined in section 3.5, the best possible value or $r^2$ can be estimated from,

$$r^2 = 1 - \frac{(n - 2)s^2}{SS_M} \qquad ...(4.23)$$

where: $SS_M$ = sum of squares about the mean for the dependent variable
n = number of (X,Y) observations
s = estimate of $\sigma$ (although in this calculation the reverse is true)

Using the the s estimate from above and the reported yield data from Table 4.4 the upper limit of $r^2$ is estimated to be,

$$r^2_{max} = 1 - \frac{(12)1.5^2}{402.7} = 0.93 \qquad ...(4.24)$$

In other words, if the error is accounted for, the highest amount of variation that the linear model could explain is 93.3%. The simulator falls short by only (93% - 83% =) 10% of the best possible fit, a further endorsement of its predictive capability.

### 4.4.5 IMPACT OF THE SIMULATOR ON QUALITY CONTROL

Figure 4.9 gives an indication of the impact of the use of the simulator on the variability of the clean coal ash results for individual shifts. The relative error of 12 hour shift results is given for each month from January, 1985 to January 1987. As indicated, the simulator was implemented in the production policy decision task in March, 1986.

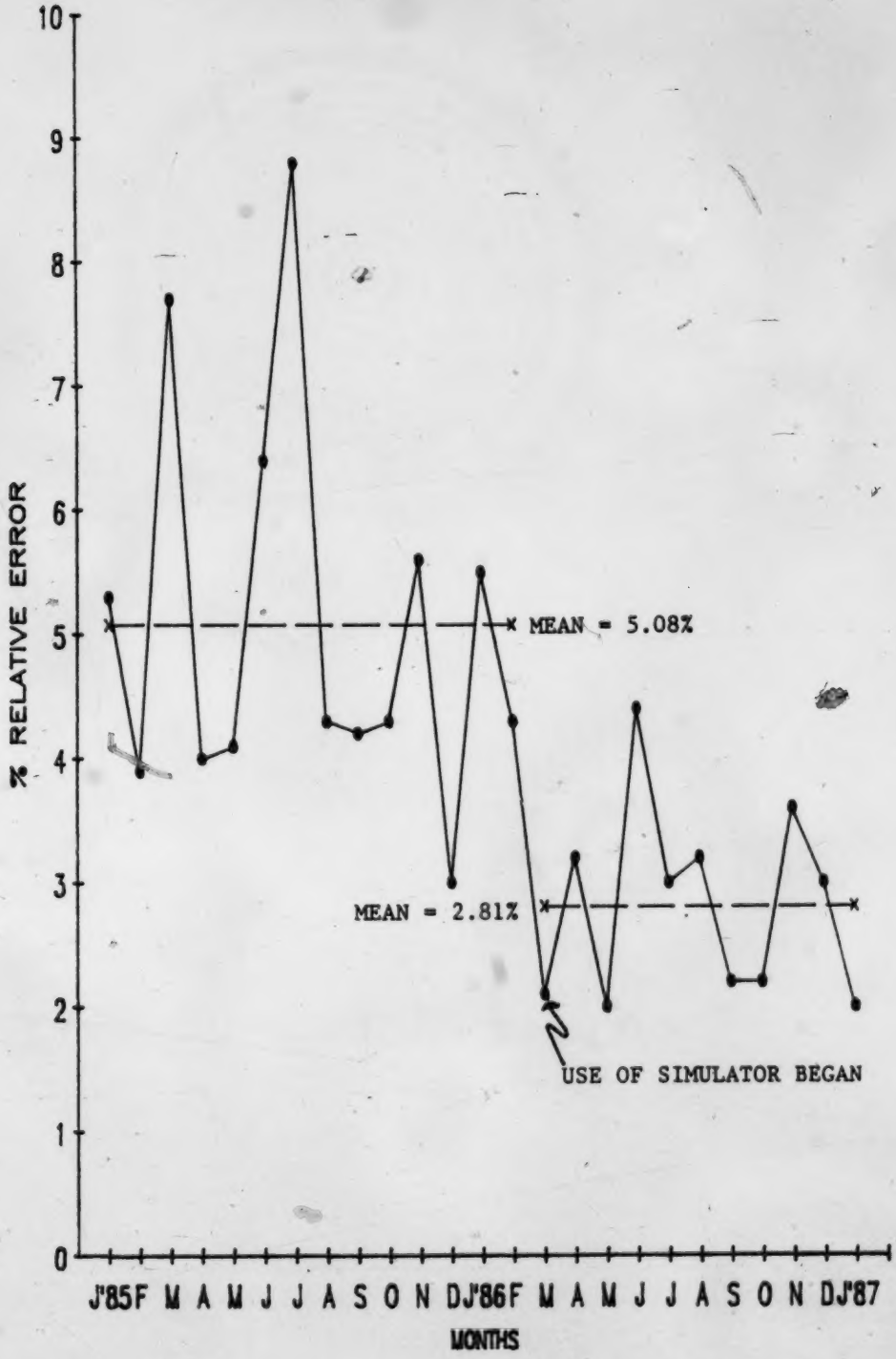



Figure 4.9 Relative Error of Shift Clean Coal Ash Results

The results are rather dramatic. The mean relative error prior to the use of the simulator was approximately 5.1%. This has been reduced to approximately 2.8% for the period that it has been in use, corresponding to a ≃70% reduction is product qualitiy variance. Based on 1986 production results this reduction in variance translates to an increase in yield of from 1.5% to 2%.

Full credit for the reduction in product variability cannot be ascribed to the use of the simulator. The whole project heightened the awareness of the operators to quality control and the importance of raw coal blending. This kind of response is typical of such projects and one can speculate that the informal feedback of information gleaned from the plant trials was at least partially responsible for the apparent reduction in variability from August, 1985 to February, 1986.

## 4.5 IMPLEMENTATION AT LINE CREEK

On a day to day basis the simulator is used to identify optimal feed blends. It also predicts the necessary cut point through the H.M. cyclones - this is subject to fine tuning based on actual clean coal (C.C.) ash results. The performance of each operating shift is also verified after completion of that shift. Actual seam blends are fed into the simulator and the clean coal ash for the shift is matched to the same value in the output (interpolation may be required) and the corresponding yield is identified.

In the long term the simulator is a very useful management tool. Given the proposed raw coal release and quality clean coal production can be anticipated and future production unit costs can be estimated. Since it gives the correlation between yield and clean coal ash levels the economic consequences of entering different markets at different ash specifications can also be determined.

The simulator has been used, as a training tool, to show operators the impact of different seams and seam blends on yield and quality. It also allows the evaluation of numerous plant feed and product quality scenarios without any actual plant testing.

To date it has given an accurate representation of plant performance. The need has not arisen to change any of its component parts (e.g. heavy media circuit, water-only cyclone circuit or flotation). As previously stated, each shift's performance is verified with the simulator and any deviation is usually explained. If a persistent yield deviation was to arise (a higher or lower yield trend) it would be quickly identified and plant observations and testing carried out to determine the cause.

Intuitively the greatest potential for improvement and consequently change exists in the flotation circuit. Efforts are constantly on-going to improve flotation yield. Any improvements would be quantified, per seam, and the simulator adjusted accordingly.

Regular plant feed sizing checks have shown that the proportion of minus 0.5 mm material has remained relatively constant. Any changes would have to be identified and incorporated in the simulator. Another potential source of error would be a change in the inherent washability of a seam or seams.

The thing to remember in terms of simulator maintenance is that, if a consistent difference between reported and simulator results is established, the full plant trials need not be repeated. The source of the difference must be identified and then only the circuit in question need be reevaluated.

# 5. CONCLUSIONS AND RECOMMENDATIONS

## 5.1 SUMMARY

The simulator has proven to be a useful tool in the following areas:

1) Maximization of plant yield and minimization of product quality variation through feed blend optimization.
2) Rationalization (reconciliation) of plant performance - it allows explanation of why yields may have been different that otherwise expected, for a given period of time.
3) Budgeting
    - estimating production unit costs based on the amount of clean coal that will be obtained from a proposed mining plan.
    - determining how well the mining plan will match customer requirements.
4) Evaluating the economic impact of different clean coal ash specifications - i.e. customers sometimes request higher or lower ash levels. The impact on yield of such a quality change can be quickly evaluated which helps in setting an acceptable selling price.
5) Training operating personnel - operators have been encouraged to run the simulator thus providing an increased understanding of how factors such as feed blend and raw coal ash affect yield and quality.

Management has developed a high level of confidence in the simulator. The predicted results are routinely used to explain past performance and predict future raw coal needs to meet customer requirements. On a recent marketing trip, the simulator and its benefits were demonstrated to prospective buyers to underscore Line Creek's commitment to optimize product yield and quality. Overall, a much better understanding of the coal preparation process at Line Creek has been achieved.

## 5.2 FUTURE WORK

The main source of difference between reported and simulator calculated yields is inaccuracy in the estimation of actual feed blends. Although the raw coal silos were designed to provide a high degree of mass flow some mixing between different layers of coal does occur. These layers typically have different ash contents and can sometimes be from different seams. Also, preferential centre draw does occur, especially when silo levels are low. As a consequence it is felt that an accurate knowledge of the material being discharged from the silos would greatly increase the accuracy of feed blend determination, thereby increasing the reliability of the simulator. This could be accomplished through the mathematical simulation of material flow through the silos, taking into consideration factors such as the seam, moisture content, weather conditions, etc. Such a study could be the subject of a separate thesis.

If an accurate silo simulator is constructed it would allow:

1) Feed blends to be optimized over much shorter intervals (e.g. 20 minutes or one hour periods as opposed to once every 12 hour shift) thus incurring a greater yield increase.
2) "Feed forward" process control to be practiced such that plant settings would be adjusted ahead of time (based on the plant simulator), in anticipation of changes in the feed.

The yield increase resulting from a much shorter optimization period is difficult to quantify. Feed forward as opposed to feed back process control will reduce the deviations of instantaneous ash results from the process average because:

1) plant settings correspond more closely to the coal being processed,
2) a trend of out of specification coal does not have to be established before plant settings are changed.

This will result in a yield gain. It will also reduce the safety margin required between average ash results and the ash limit (incurring an additional yield gain).

The impact of instantaneous ash deviations from the process average is given below. The tonnage loss (L) resulting from instantaneous deviations can be approximated from the following formula (16):

$$L = F\left[\bar{Y}(t_x + t_y) - Y_x t_x - Y_z t_z\right] \qquad ...(5.1)$$

where: F = solids mass flow rate to the process
$\bar{Y}$ = yield on the yield-ash curve corresponding to the average process ash ($\bar{A}$)
$(A_x, Y_x)$ = average overcleaning point
$(A_z, Y_z)$ = average undercleaning point
$(t_x, t_z)$ = duration of overcleaning and undercleaning respectively

From actual operating data let $A_x = 8.52\%$ and $A_z = 10.21\%$. Then from the yield-ash curve, $Y_x = 55.58\%$ and $Y_z = 69.93\%$, therefore,

$$\bar{A} = \frac{0.556(8.52) + 0.70(10.21)}{0.556 + 0.70} = 9.46\% \qquad ...(5.2)$$

and from the yield-ash curve, $\bar{Y} = 65.5\%$. Using this data and assuming $t_x = t_z = 0.5h$, and F = 380 tph, the yield loss from equation (5.1) is 10.5 tph or 2.77%.

By contrast, if about 65% of the instantaneos ash deviations can be eliminated, the loss will be 1.56 tph or 0.41% where $A_x = 9.10\%$, $A_z = 9.83\%$, $Y_x = 62.61\%$ and $Y_z = 67.89\%$ with $\bar{A} = 9.48\%$ and $\bar{Y} = 65.66\%$. Therefore, the net yield improvement will be 2.36%.

The use of an on-stream ash analyser to continuously measure the raw coal ash going into the silos would enhance the use of the silo simulator and feed forward process control. However, such an installation would have to be justified on the basis of potential economic gain.

An on-stream ash analyser on the product to provide quick clean coal ash results would be a good check of the feed forward control strategy and allow fine tuning of the

process variables. None-the-less an economic justifcation would also be required.

## 6. REFERENCES


1) Pearson D.E.
The Quality of Western Canadian Coking Coal
CIM Bull., Jan., 1980, pg. 70

2) Romero D.L., Van Koughnett L.
Dust Control at the Line Creek Mine
CIM Third Coal Operators Conference, Fernie, B.C., Sept. 26-28, 1984

3) Van den Broek J.J.M.
Line Creek Mine: Coal Processing and Quality Control
Mineral Beneficiation Conference, Nagasaki, Japan, June 13-14, 1984, pg. 172

4) Leonard J.W., Ed.
Coal Preparation Chapter 18: 4th Edition
AIME, New York, 1979

5) Horsfall D.W.
Washery Efficiency and its Financial Implications
Coal, Gold & Base Minerals, August, 1977

6) Sokaski, M., Jacobsen P.S., Geer M.R.
Performance of Baum Jigs in Treating Rocky Mountain Coals
U.S. Bureau of Mines Report No. 6306, 1963

7) Gottfried B.S.
A Generalization of Distribution Data for Characterizing the Performance of Float-Sink Coal Cleaning Devices
Int. J. Min. Proc., Vol. 6, 1978, pg. 1

8) Pauncz I., Stockton N.D., LePage A.J.
Prediction of Washery Performance Using Computer Simulation Techniques
Second Australian Coal Prep. Conference, 1983, pg. 444

9) Kelly E.G., Spottiswood D.J.
Prediction and Analysis of Plant Peformance
Mineral & Energy Resources, Vol. 26, No. 3, May, 1983

10) Davis J.J., Wood C.J., Lyman G.J.
Effects of Operating Variables on Dense Medium Cyclone

Operation
Third Australian Coal Prep. Conference, 1985, pg. 107

12) Meloy T.P.
Analysis and Optimization of Mineral Processing and Coal Cleaning Circuits - Circuit Analysis
Int. J. Min. Proc., Vol 10, 1983, pg. 61

13) Kapur P.C.
A Fast Numerical Method for Evaluating the Performance of Float-Sink Coal Cleaning Equipment
Int. J. Min. Proc., Vol. 10, 1983, pg. 81

14) Absil J.H., Keuning W., Meerman P.G.
Prediction of Washery Plant Performance by Data Processing
Fifth International Coal Prep. Congress, pg. 381

15) Salama A.I.A., Mikhail M.
Optimization of Coal or Mineral Circuits
Third Conference on the Use of Computers in the Coal Industry
MorganTown, W.V., July 28-30, 1986

16) Cierpisz S., Gottfried B.S.
Theoretical Aspects of Coal Washer Performance
Int. J. Min. Proc., Vol. 4, 1977, pg. 261

17) Plitt, L.R., Flintoff B.C.
Modelling and Control of Coal Beneficiation Unit Operations
ERRF Project U-28, Dept. Min. Engng., Univ. Alberta, 1983

18) Mular A.L.
Empirical Modelling and Optimization of Mineral Processes
Minerals Sci. Engng., Vol. 4, No. 3, July, 1972, pg. 30

19) Walters A.D., Ramani R.V.
A Review of Computer Oriented Models of Coal Preparation Plants
South Africa

20) Abara J.A., Gottfried B.S.

Maximization of Yields of Clean Coal from Coal Preparation Plants
Ind. Eng. Chem. Process Des. Dev., Vol. 18, No. 3, 1979, pg. 511

21) Wizzard J.T., Killmeyer R.P., Gottfried B.S.
Computer Program for Evaluating Coal Washer Performance
Mining Engineering, March, 1983, pg. 252

22) Peng F.F.
Graphic Routine and Digital 'Simulation the Aids in Prediction of Coal Preparation Plant Performance and Yield Optimization
First Conference Use of Computers in Coal Industry, AIME, 1983, pg. 187

23) Trawinski H.
The Mathematical Simulation of Tromp Curve
Interceram, NR .1, W. Germany, 1978, pg. 21

24) Erasmus T.C.
Predicting the Performance of a Coal Washer with the Aid of a Mathematical Model
Fuel Research Institute, Pretoria, S.A.

25) Walters A.D., Ramani R.V.
The Optimization of Coal Preparation Plant Yields Using Computer Programming
7th Int. Coal Preparation Congress, Sydney, 1976

26) Turak A.A.
Mathematical Modeliing of Automedium Cyclones
M. Sc. Thesis, Dept. of Min. Engng., U. of Alberta, 1985

27) Gottfried B.S., Abara J.
Computer Simulation of Coal Preparation Plants
Computer and Chemical Engng., Vol. 2, 1978, pg. 99

28) Firth B.A., Grill C., Janssen E., Weale W.
Computer Simulation of Coal Preparation and Its Application at the Saxonvale Mine
Second Australian Coal Prep. Conference, 1983, pg. 421

29) Walter G.W., Whiten W.J.
An Examination of Tertiary Screening Using Simulation

Dept. of Mining and Met. Engng., Univ. Queensland, Australia, July, 1976, pg. 276

30) Osborne D.G.
Rotary Vacuum Filtration of Coal Flotation Concentrates
Int. J. Min. Proc., Vol. 3, 1976, pg. 175

31) Peng F.F.
Coal Cleaning and Dewatering Circuits Their Mathematical Modelling and Economic Evaluating
Fourth Joint Meeting MMIJ-AIME, Tokyo, 1980, pg. 33

32) Tierney J.W., Gottfried B.S., Zhao G.Q.
A Simulator for Dewatering of Coal Fines
First Conference Use of Computers in Coal Industry, AIME, 1983, pg. 230

33) Wilhelm J.H., Naide Y.
Sizing and Operating Continuous Thickeners
Envirotech Corp., Salt Lake City

34) Weyher L.H.E.
Computer Assistance in the Analysis and Development of Coal Beneficiation Flowsheets
Mining Congress Journal, Jan., 1971, pg. 38

35) Gottfried B.S.
Computer Simulation of Coal Preparation Plants
Univ. Pitt., EPA Report 600/7-78-211, November, 1978

36) Goodman F.K., McCreery J.H.
Coal Preparation Plant Computer Model: Volume 1. User Manual
Battelle Memorial Institute, EPA Report 600/7-80-010a, January, 1980

37) Chaves M.M., Gottfried B.S.
Micro Computer Simulation of Coal Preparation Plants
First Conference Use of Computers in Coal Industry, AIME, 1983, pg. 173

38) Messenger P., Hampel B.W.
Computer Simulation of Coal Preparation Processes
Chemical Engineering in Australia, Vol. Ch. E9, No. 2, June, 1984, pg. 32

39) Laguitton D. (Editor)
40) The SPOC Manual: Chapter 5.1 Unit Models (Part B)
CANMET Report SP85-1/5.1E, 1985

41) Zigmond, R.D., Ramani R.V., Frantz R.L.
A Computer Program for the Analyses of Coal Preparation Plant Economics
AIME Annual Meeting, Chicago, Feb. 22-26, 1981

42) Wagner H.M.
Principles of Operations Research: 2nd Edition
Prentice-Hall, Englewood Cliffs, N.J., 1975, pg. 31

43) Wright F.D.
Maximizing the Profit of a Coal Preparation Plant by Linear Programming
AIME Transactions, Vol. 220, 1961, pg. 82

44) Butcher S.G., Beninger B.L.
Optimization of Proceeds in Changing Market and Mining Conditions
CIM Bull., July, 1979, pg. 143

45) Salama A.I.A.
Yield Maximization in Coal Blending
10th Internatioonal Coal Preparation Congress, Edmonton, 1986, pg. 196

46) Bowen R.M., Jowett A., Smith H.W.
Calculations for Complex Coal Cleaning
Third Australian Coal Prep. Conference, 1985, pg. 205

47) Salama A.I.A., Mikhail M.W., Mikula, R.J.
Coal Preparation Computer Applications
85th Annual General Meeting of CIM, Winnipeg, April 17-20, 1983

48) Crowden H., Smith K.
Optimization of Yield and Quality Using On-Line Ash Monitors
Third Australian Coal Prep. Conference, 1985, pg. 222

49) Lyman G.J., Denney B.D.
Advances in Coal Preparation and Automatic Control in Australia

ICCA Conference, Pretoria, S.A., Oct., 1985, pg. 67

50) Mikhail M.W., Picard J.L., Humenniuk, O.E.
Performance Evaluation of Gravity Separators in Canadian Washeries
CIM Second Technical Conference on Western Canadian Coals Edmonton, June 3-5, 1982

51) Clarkson G.J., Hornsby D.T., Walker D.J.
Automatic Flotation Control Using On-Stream Ash Analysis
Third Australian Coal Prep. Conference, 1985, pg. 239

52) Economics of On-Line Blending
Report No. 1330-47, Science Applications International Corp., Sunnyvale, CA.

53) Cooper H.R.
On-Line Coal Analysis Promises to Improve Profitability
Coal Mining & Processing, Sept.,1983, pg. 53

54) Annual Book of ASTM Standards, Part 26
ASTM, Philadelphia, 1977

55) Plitt L.R., Flintoff B.C.
Analysis, Optimization and Control of Mineral Processes
Int. Report, Dept. Min. Engng., Univ. Alberta, June, 1979

56) Shea S.C., Sehgal R.S.
Automatic Product - Quality Control for Coal Cleaning Plants
Praxis Engineers, Inc., Milpitas, California

57) Booth T.L., Chien Y.T.
Computing Fundamentals and Applications
Hamilton Publishing Co., Santa Barbara, California, 1974, pg. 250

58) Fisher R.A., Yates F.
Statistical Tables for Biological, Agricultural and Medical Research
Oliver & Boyd Ltd., Edinburgh and London, 1953

59) Draper N.R., Smith H.

Applied Regression Anlaysis
Wiley & Sons, 1966

# 7. APPENDIX 1

## 7.1 DESCRIPTION OF SAMPLING POINTS FOR PLANT TRIALS

| | Name | Type | Top Size (mm) | Sets of cuts | No.of increments per cut | Total no.of increments | Approx. wt. of samples (Kg) |
|---|---|---|---|---|---|---|---|
| 1. | Plant feed | bulk | 50 | 10 | 1 | 10 | 500 |
| 2. | Heavy media cyclone feed | bulk | 50 | 10 | 4 | 40 | 120 |
| 3. | Heavy media cyclone product | bulk | 50 | 10 | 4 | 40 | 120 |
| 4. | Heavy media cyclone reject | bulk | 50 | 10 | 2 | 20 | 100 |
| 5. | Water only cyclone feed | slurry | 0.5 | 10 | 2 | 20 | 2.8 |
| 6. | Water only cyclone product | slurry | 0.5 | 10 | 2 | 20 | 1.2 |
| 7. | Water only cyclone reject | slurry | 0.5 | 10 | 20 | 200 | 25 |
| 8. | Sec.Water only clyclone product | slurry | 0.5 | 10 | 2 | 20 | 0.3 |
| 9. | Sec.Water only cyclone reject | slurry | 0.5 | 10 | 2 | 20 | 9 |
| 10. | Sieve bend feed | slurry | 0.5 | 10 | 2 | 20 | 2.6 |
| 11. | Sieve bend oversize | slurry | 0.5 | 10 | 6 | 60 | 17 |
| 12. | Flotation feed Sieve bend undersize | slurry | 0.4 | 10 | 2 | 20 | 1.3 |
| 13. | Flotation product | slurry | 0.4 | 10 | 12 | 120 | 2.3 |
| 14. | Flotation tailing | slurry | 0.4 | 10 | 2 | 20 | 1.5 |
| 15. | Fines product | bulk | 0.5 | 10 | 2 | 20 | 75 |
| 16. | Plant product | bulk | 50 | 3 | 1 | 3 | 200 |

Description of sampling points

1. Plant feed- full belt cuts were taken with a conveyor sampler.

2. Heavy media cyclone feed- all four deslime screen oversize streams were sampled with a shovel. The full width of each screen was taken.

3. Heavy media cyclone product- all four clean coal drain and rinse screens were sampled with a shovel. The full width of each screen was taken.

4. Heavy media cyclone reject- both reject drain and rinse screens were sampled with a shovel. The full width of each screen was taken.

5. Water only cyclone feed- half of the total stream was sampled with a bucket.

6. Water only cyclone product- half of the stream was sampled with a hand held cutter.

7. Water only cyclone reject- twenty (those operating) water only cyclones were sampled with a hand held cutter.

8. Secondary water only cyclone product- four out of the six cyclones were sampled with a hand held cutter.

9. Secondary water only cyclone reject- the total stream was sampled with a hand held cutter.

10. Sieve bend feed- the total stream was sampled with a bucket.

11. Sieve bend overflow- the full width of all six secondary sieve bends were sampled with a hand held cutter.

12. Flotation feed- both flotation feed lines were sampled with a bucket.

13. Flotation product- all 12 flotation cells were sampled with a hand held cutter. The full length of each cell was taken.

14. Flotation tailing- both flotation tailing lines were sampled with a bucket.

15. Fine product- two of the three screen bowl centrifuges were sampled. The third centrifuge product stream is not accessible.

16. Plant product- full belt cuts were taken with a full stream conveyor sampler. One cut per hour for a total of three was the maximum possible without interfering with regular product sampling.

It is worth noting that H.M. Cyclone; feed, product and reject samples satisfy A.S.T.M. requirements (document 02234) (52) for number of increments and sample size. Some of the slurry streams, such as the secondary water only cyclone product, provided relatively small samples due to the very dilute nature of these slurries.

| Sample | % Solids | % Air dry loss | % Res. Moist. | % Total Moist. | % Ash | F.S.I. | | + 1/4" | 1/4" x 28m | 28m x 100m | 100m x 200m | 200m x 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. Plant Feed | - | 3.08 | 1.11 | 4.19 | 39.42 | 2.5 | % Weight | 35.80 | 41.98 | 16.18 | 4.87 | 1.17 |
| | | | | | | | % Ash | 53.57 | 33.61 | 21.88 | 20.29 | 21.42 |
| | | | | | | | F.S.I. | 1.0 | 4.0 | 5.5 | 6.0 | 4.0 |
| 2. H.M. Feed | - | - | 0.92 | - | 40.82 | 2.5 | % Weight | 43.35 | 51.99 | 4.33 | 0.18 | 0.15 |
| | | | | | | | % Ash | 58.96 | 34.04 | 22.26 | 14.94 | 20.64 |
| | | | | | | | F.S.I. | 1.0 | 3.5 | 7.5 | 6.0 | 4.5 |
| 3. H.M. Product | - | - | 0.94 | - | 11.15 | 7.5 | % Weight | 28.43 | 68.75 | 2.32 | 0.26 | 0.24 |
| | | | | | | | % Ash | 15.41 | 9.73 | 8.80 | 8.81 | 14.34 |
| | | | | | | | F.S.I. | 3.0 | 8.5 | 9.0 | 8.0 | 6.5 |
| 4. H.M. Reject | - | - | 0.86 | - | 61.54 | 1.0 | % Weight | 49.11 | 49.23 | 1.36 | 0.15 | 0.15 |
| | | | | | | | % Ash | 63.62 | 56.61 | 48.32 | 29.55 | 40.09 |
| | | | | | | | F.S.I. | 1.0 | 1.0 | 1.5 | 3.0 | 1.0 |
| 5. W.O. Cy.Feed | 9.26 | - | 0.92 | - | 23.59 | 5.5 | % Weight | 0.0 | 22.69 | 57.88 | 12.69 | 6.74 |
| | | | | | | | % Ash | - | 26.38 | 22.44 | 21.97 | 29.57 |
| | | | | | | | F.S.I. | - | 7.0 | 7.0 | 5.5 | 2.0 |
| 6. W.O. Cy. Product | 5.58 | - | 1.15 | - | 16.84 | 7.5 | % Weight | 0.0 | 11.68 | 59.65 | 16.59 | 12.08 |
| | | | | | | | % Ash | - | 8.81 | 14.39 | 21.60 | 27.27 |
| | | | | | | | F.S.I. | - | 9.0 | 8.0 | 4.5 | 1.0 |
| 7. W.O. Cy. Reject | 61.26 | - | 1.08 | - | 54.30 | 1.0 | % Weight | 0.0 | 49.38 | 45.70 | 3.56 | 1.36 |
| | | | | | | | % Ash | - | 47.30 | 61.13 | 60.45 | 44.94 |
| | | | | | | | F.S.I. | - | 1.0 | 1.0 | 1.0 | 1.0 |
| 8. Sec.W.O. Cy.Product | 1.33 | - | 1.13 | - | 20.89 | 1.0 | % Weight | 0.0 | 1.97 | 88.10 | 8.22 | 1.71 |
| | | | | | | | % Ash | - | 14.88 | 20.31 | 27.25 | 22.81 |
| | | | | | | | F.S.I. | - | I.S. | 1.0 | 1.0 | I.S. |

| Sample | % Solids | % Air dry loss | % Res. Moist. | % Total Moist. | % Ash | F.S.I. | | + 1/4" | 1/4" x 28m | 28m x 100m | 100m x 200m | 200m x 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 9. Sec.W.O. Cy.Reject | 67.29 | - | 0.94 | - | 61.12 | 1.0 | % Weight | 0.44 | 48.98 | 48.36 | 1.95 | 0.27 |
| | | | | | | | % Ash | 62.86 | 51.49 | 69.72 | 76.45 | 59.08 |
| | | | | | | | F.S.I. | 0.5 | 1.0 | 0.5 | 0.0 | 0.0 |
| 10.S.B. Feed | 7.39 | - | 1.13 | - | 15.45 | 7.5 | % Weight | 0.0 | 16.17 | 61.58 | 18.93 | 3.32 |
| | | | | | | | % Ash | - | 8.00 | 14.25 | 22.98 | 29.64 |
| | | | | | | | F.S.I. | - | 8.5 | 8.0 | 5.0 | 2.0 |
| 11.S.B. Oversize | 21.37 | - | 1.03 | - | 12.03 | 8.5 | % Weight | 0.0 | 35.87 | 56.69 | 4.66 | 2.78 |
| | | | | | | | % Ash | - | 8.11 | 13.26 | 21.14 | 26.03 |
| | | | | | | | F.S.I. | - | 8.0 | 8.0 | 6.0 | 4.5 |
| 12.Flotation Feed | 3.32 | - | 1.18 | - | 20.91 | 4.5 | % Weight | 0.0 | 0.4 | 43.84 | 31.59 | 24.17 |
| | | | | | | | % Ash | - | 16.04 | 16.08 | 21.46 | 27.23 |
| | | | | | | | F.S.I. | - | I.S. | 7.5 | 4.0 | 1.0 |
| 13.Flotation Product | 17.49 | - | 1.11 | - | 6.8 | 7.0 | % Weight | 0.0 | 0.0 | 20.06 | 44.01 | 35.93 |
| | | | | | | | % Ash | - | - | 6.39 | 6.68 | 7.29 |
| | | | | | | | F.S.I. | - | - | 7.0 | 7.0 | 7.5 |
| 14.Flotation Product | 3.52 | - | 1.10 | - | 24.01 | 4.0 | % Weight | 0.0 | 0.68 | 53.25 | 26.86 | 19.21 |
| | | | | | | | % Ash | - | 29.87 | 19.58 | 27.12 | 33.27 |
| | | | | | | | F.S.I. | - | I.S. | 5.5 | 4.0 | 1.0 |
| 15.Fines Product | - | 12.73 | 0.86 | 13.59 | 11.95 | 8.5 | % Weight | 0.0 | 15.34 | 67.47 | 13.44 | 3.75 |
| | | | | | | | % Ash | - | 7.82 | 12.79 | 14.12 | 13.30 |
| | | | | | | | F.S.I. | - | 9.0 | 8.5 | 8.0 | 7.5 |
| 16.Plant Product | - | 6.28 | 1.15 | 7.43 | 11.67 | 8.0 | % Weight | 20.92 | 51.08 | 24.86 | 2.65 | 0.49 |
| | | | | | | | % Ash | 16.20 | 10.36 | 11.64 | 12.11 | 11.56 |
| | | | | | | | F.S.I. | 2.5 | 8.0 | 8.5 | 8.0 | 7.5 |

NOTE: All Ash results calculated to dry basis
I.S. - insufficient sample

| Sample | % Solids | % Air dry loss | % Res. Moist. | % Total Moist. | % Ash | F.S.I. | | + 1/4" | 1/4" x 28m | 28m x 100m | 100m x 200m | 200m x 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. Plant Feed | - | 2.97 | 0.97 | 3.94 | 19.74 | 3.0 | % Weight | 47.17 | 35.29 | 11.14 | 4.45 | 1.95 |
| | | | | | | | % Ash | 24.45 | 16.43 | 12.85 | 12.82 | 13.01 |
| | | | | | | | F.S.I. | 1.5 | 6.0 | 6.0 | 7.0 | 4.0 |
| 2. H.M. Feed | - | - | 0.89 | - | 19.59 | 2.0 | % Weight | 50.12 | 47.43 | 1.96 | 0.24 | 0.25 |
| | | | | | | | % Ash | 21.44 | 15.87 | 13.18 | 9.90 | 13.02 |
| | | | | | | | F.S.I. | 1.5 | 3.5 | 3.0 | 3.5 | 2.0 |
| 3. H.M. Product | - | - | 1.00 | - | 7.84 | 3.5 | % Weight | 53.66 | 44.32 | 1.44 | 0.28 | 0.30 |
| | | | | | | | % Ash | 8.99 | 6.20 | 5.99 | 6.12 | 11.77 |
| | | | | | | | F.S.I. | 1.5 | 7.0 | 8.0 | 7.5 | 4.5 |
| 4. H.M. Reject | - | - | 0.84 | - | 42.54 | 1.0 | % Weight | 58.35 | 40.20 | 1.04 | 0.18 | 0.23 |
| | | | | | | | % Ash | 54.68 | 40.82 | 27.31 | 21.87 | 22.11 |
| | | | | | | | F.S.I. | 1.0 | 1.0 | 1.5 | 2.5 | 2.0 |
| 5. W.O. Cy.Feed | 8.74 | - | 0.90 | - | 14.61 | 5.0 | % Weight | 0.0 | 26.33 | 45.84 | 14.16 | 13.67 |
| | | | | | | | % Ash | - | 13.27 | 13.31 | 13.71 | 19.24 |
| | | | | | | | F.S.I. | - | 7.5 | 7.0 | 6.5 | 2.0 |
| 6. W.O. Cy. Product | 5.32 | - | 1.18 | - | 11.25 | 5.5 | % Weight | 0.0 | 13.83 | 50.07 | 19.40 | 16.70 |
| | | | | | | | % Ash | - | 5.73 | 9.11 | 13.93 | 18.84 |
| | | | | | | | F.S.I. | - | 8.0 | 6.0 | 6.0 | 1.5 |
| 7. W.O. Cy. Reject | 54.00 | - | 0.91 | - | 39.82 | 1.5 | % Weight | 0.0 | 53.15 | 41.18 | 4.07 | 1.60 |
| | | | | | | | % Ash | - | 29.46 | 50.25 | 49.16 | 50.40 |
| | | | | | | | F.S.I. | - | 2.0 | 1.0 | 2.0 | 1.0 |
| 8. Sec.W.O. Cy.Product | 0.58 | - | 1.07 | - | 16.02 | 3.5 | % Weight | I.S. | I.S. | I.S. | I.S. | I.S. |
| | | | | | | | % Ash | - | - | - | - | - |
| | | | | | | | F.S.I. | - | - | - | - | - |

| Sample | % Solids | % Air dry loss | % Res. Moist. | % Total Moist. | % Ash | F.S.I. | | + 1/4" | 1/4" x 28m | 28m x 100m | 100m x 200m | 200m x 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 9. Sec.W.O. Cy.Reject | 60.80 | - | 0.74 | - | 49.11 | 1.0 | % Weight | 0.0 | 56.97 | 40.34 | 2.34 | 0.35 |
| | | | | | | | % Ash | - | 37.38 | 66.79 | 77.63 | 63.88 |
| | | | | | | | F.S.I. | - | 1.0 | 0.5 | 0.0 | 1.0 |
| 10.S.B. Feed | 10.02 | - | 0.92 | - | 9.84 | 6.5 | % Weight | 0.0 | 29.48 | 48.52 | 11.63 | 10.36 |
| | | | | | | | % Ash | - | 5.71 | 9.38 | 13.43 | 17.65 |
| | | | | | | | F.S.I. | - | 8.0 | 7.0 | 5.0 | 2.0 |
| 11.S.B. Oversize | 16.46 | - | 0.81 | - | 8.24 | 7.5 | % Weight | 0.0 | 30.73 | 56.82 | 7.50 | 4.95 |
| | | | | | | | % Ash | - | 5.57 | 8.26 | 13.15 | 16.01 |
| | | | | | | | F.S.I. | - | 8.0 | 7.5 | 6.0 | 3.0 |
| 12.Flotation Feed | 4.02 | - | 0.87 | - | 13.20 | 4.5 | % Weight | 0.0 | 1.10 | 46.76 | 30.65 | 21.49 |
| | | | | | | | % Ash | - | 6.72 | 10.56 | 14.23 | 18.05 |
| | | | | | | | F.S.I. | - | 6.0 | 7.0 | 5.0 | 1.0 |
| 13.Flotation Product | 25.5 | - | 0.75 | - | 9.53 | 5.0 | % Weight | 0.0 | 0.59 | 38.73 | 29.57 | 31.11 |
| | | | | | | | % Ash | - | 6.01 | 7.76 | 8.79 | 12.06 |
| | | | | | | | F.S.I. | - | 7.5 | 7.5 | 7.0 | 2.0 |
| 14.Flotation Product | 1.37 | - | 0.94 | - | 32.44 | 1.0 | % Weight | 0.0 | 0.0 | 34.23 | 23.27 | 42.50 |
| | | | | | | | % Ash | - | - | 26.51 | 33.55 | 35.98 |
| | | | | | | | F.S.I. | - | - | 2.0 | 1.5 | 1.0 |
| 15.Fines Product | - | 13.45 | 0.96 | 14.41 | 8.22 | 7.0 | % Weight | 0.0 | 14.48 | 54.93 | 18.34 | 12.15 |
| | | | | | | | % Ash | - | 5.37 | 7.89 | 9.21 | 11.24 |
| | | | | | | | F.S.I. | - | 8.0 | 8.0 | 8.0 | 5.5 |
| 16.Plant Product | - | 10.06 | 0.98 | 11.04 | 8.06 | 4.5 | % Weight | 30.00 | 34.59 | 19.54 | 8.54 | 7.33 |
| | | | | | | | % Ash | 9.71 | 6.18 | 7.46 | 8.45 | 11.00 |
| | | | | | | | F.S.I. | 1.5 | 5.5 | 7.5 | 7.5 | 5.5 |

NOTE: All Ash results calculated to dry basis

| Sample | % Solids | % Air dry loss | % Res. Moist. | % Total Moist. | % Ash | F.S.I. | | + 1/4" | 1/4" x 28m | 28m x 100m | 100m x 200m | 200m x 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. Plant Feed | - | 8.32 | 0.85 | 9.17 | 27.37 | 3.0 | % Weight | 48.05 | 35.83 | 9.53 | 3.67 | 2.92 |
| | | | | | | | % Ash | 38.41 | 19.71 | 15.32 | 15.38 | 15.55 |
| | | | | | | | F.S.I. | 1.0 | 4.5 | 7.5 | 6.5 | 6.5 |
| 2. H.M. Feed | - | - | 0.66 | - | 25.58 | 4.0 | % Weight | 54.08 | 42.19 | 3.16 | 0.34 | 0.23 |
| | | | | | | | % Ash | 41.18 | 20.31 | 15.53 | 11.36 | 14.50 |
| | | | | | | | F.S.I. | 2.0 | 5.0 | 8.0 | 8.0 | 7.0 |
| 3. H.M. Product | - | - | 0.82 | - | 8.94 | 4.5 | % Weight | 41.78 | 55.48 | 2.35 | 0.23 | 0.16 |
| | | | | | | | % Ash | 10.64 | 8.31 | 7.56 | 9.25 | 15.84 |
| | | | | | | | F.S.I. | 2.0 | 6.5 | 8.5 | 7.5 | 6.5 |
| 4. H.M. Reject | - | - | 1.07 | - | 71.13 | 1.0 | % Weight | 76.37 | 22.74 | 0.60 | 0.14 | 0.15 |
| | | | | | | | % Ash | 78.27 | 64.17 | 46.06 | 40.41 | 41.07 |
| | | | | | | | F.S.I. | 0.0 | 0.5 | 1.5 | 3.0 | 1.0 |
| 5. W.O. Cy.Feed | 8.24 | - | 0.86 | - | 17.12 | 7.0 | % Weight | 0.0 | 23.66 | 48.12 | 17.84 | 10.38 |
| | | | | | | | % Ash | - | 18.06 | 16.13 | 17.02 | 21.02 |
| | | | | | | | F.S.I. | - | 6.5 | 7.0 | 7.0 | 4.0 |
| 6. W.O. Cy. Product | 6.85 | - | 0.98 | - | 13.15 | 6.5 | % Weight | 0.0 | 12.63 | 49.00 | 27.16 | 11.21 |
| | | | | | | | % Ash | - | 6.96 | 10.66 | 16.71 | 22.03 |
| | | | | | | | F.S.I. | - | 8.5 | 8.5 | 6.0 | 2.0 |
| 7. W.O. Cy. Reject | 58.6 | - | 0.84 | - | 48.29 | 1.5 | % Weight | 0.0 | 41.04 | 52.10 | 5.29 | 1.57 |
| | | | | | | | % Ash | - | 37.33 | 55.62 | 56.99 | 50.49 |
| | | | | | | | F.S.I. | - | 2.0 | 1.0 | 2.0 | 2.0 |
| 8. Sec.W.O. Cy.Product | 1.59 | - | 0.91 | - | 21.39 | 4.0 | % Weight | 0.0 | 24.03 | 53.08 | 17.22 | 5.67 |
| | | | | | | | % Ash | - | 10.47 | 23.28 | 27.64 | 19.49 |
| | | | | | | | F.S.I. | - | 7.0 | 3.0 | 1.5 | 1.5 |

| Sample | % Solids | % Air dry loss | % Res. Moist. | % Total Moist. | % Ash | F.S.I. | | + 1/4" | 1/4" x 28m | 28m x 100m | 100m x 200m | 200m x 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 9. Sec.W.O. Cy.Reject | 66.04 | - | 0.82 | - | 56.56 | 1.0 | % Weight | 0.44 | 45.94 | 50.18 | 3.48 | 0.40 |
| | | | | | | | % Ash | - | 42.99 | 67.86 | 79.85 | 75.72 |
| | | | | | | | F.S.I. | - | 1.0 | 0.5 | 0.0 | 0.0 |
| 10.S.B. Feed | 8.59 | - | 0.82 | - | 13.92 | 7.0 | % Weight | 0.0 | 16.41 | 51.53 | 20.49 | 11.57 |
| | | | | | | | % Ash | - | 6.80 | 10.79 | 16.96 | 28.58 |
| | | | | | | | F.S.I. | - | 8.0 | 8.0 | 6.0 | 3.5 |
| 11.S.B. Oversize | 21.05 | - | 0.68 | - | 8.76 | 8.0 | % Weight | 0.0 | 33.72 | 54.19 | 8.38 | 3.71 |
| | | | | | | | % Ash | - | 6.37 | 8.74 | 14.19 | 16.37 |
| | | | | | | | F.S.I. | - | 8.0 | 8.0 | 7.5 | 6.5 |
| 12.Flotation Feed | 4.57 | - | 0.85 | - | 13.76 | 7.0 | % Weight | 0.0 | 2.90 | 43.10 | 24.65 | 29.35 |
| | | | | | | | % Ash | - | 6.60 | 10.01 | 13.74 | 20.18 |
| | | | | | | | F.S.I. | - | 8.5 | 8.5 | 7.5 | 3.0 |
| 13.Flotation Product | 29.51 | - | 1.0 | - | 6.11 | 9.0 | % Weight | 0.0 | 1.49 | 38.87 | 27.02 | 32.62 |
| | | | | | | | % Ash | - | 4.52 | 5.06 | 5.59 | 8.02 |
| | | | | | | | F.S.I. | - | 9.0 | 9.0 | 8.5 | 7.0 |
| 14.Flotation Product | 2.81 | - | 1.02 | - | 21.20 | 4.0 | % Weight | 0.0 | 4.72 | 44.14 | 25.36 | 25.78 |
| | | | | | | | % Ash | - | 11.79 | 15.99 | 22.79 | 30.56 |
| | | | | | | | F.S.I. | - | 7.0 | 6.5 | 4.0 | 1.0 |
| 15.Fines Product | - | 13.63 | 0.92 | 14.55 | 7.84 | 9.0 | % Weight | 0.0 | 12.44 | 50.22 | 17.75 | 19.59 |
| | | | | | | | % Ash | - | 11.79 | 15.99 | 22.79 | 30.56 |
| | | | | | | | F.S.I. | - | 7.0 | 6.5 | 4.0 | 1.0 |
| 16.Plant Product | - | 10.29 | 0.64 | 10.93 | 8.81 | 5.0 | % Weight | 43.55 | 35.35 | 11.66 | 7.15 | 2.29 |
| | | | | | | | % Ash | 10.91 | 8.41 | 6.99 | 7.33 | 10.00 |
| | | | | | | | F.S.I. | 2.5 | 6.5 | 9.0 | 8.5 | 7.5 |

NOTE: All Ash results calculated to dry basis

| Sample | % Solids | % Air dry loss | % Res. Moist. | % Total Moist. | % Ash | F.S.I. | | + 1/4" | 1/4" x 28m | 28m x 100m | 100m x 200m | 200m x 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. Plant Feed | - | 1.97 | 0.73 | 2.70 | 29.97 | 3.0 | % Weight | 45.98 | 36.24 | 11.19 | 3.49 | 3.10 |
| | | | | | | | % Ash | 41.66 | 24.14 | 17.33 | 15.68 | 16.95 |
| | | | | | | | F.S.I. | 1.0 | 4.5 | 7.0 | 8.0 | 5.0 |
| 2. H.M. Feed | - | - | 0.83 | - | 32.21 | 3.0 | % Weight | 43.69 | 51.25 | 4.28 | 0.46 | 0.32 |
| | | | | | | | % Ash | 41.88 | 23.77 | 16.59 | 11.62 | 14.47 |
| | | | | | | | F.S.I. | 1.0 | 5.5 | 8.0 | 8.5 | 6.5 |
| 3. H.M. Product | - | - | 0.75 | - | 11.47 | 7.0 | % Weight | 43.04 | 54.40 | 2.04 | 0.36 | 0.16 |
| | | | | | | | % Ash | 13.58 | 10.60 | 9.63 | 9.02 | 11.10 |
| | | | | | | | F.S.I. | 4.0 | 7.5 | 9.0 | 9.0 | 8.0 |
| 4. H.M. Reject | - | - | 0.81 | - | 67.64 | 0.5 | % Weight | 75.41 | 21.32 | 0.85 | 0.18 | 0.24 |
| | | | | | | | % Ash | 76.16 | 58.95 | 44.85 | 37.76 | 35.45 |
| | | | | | | | F.S.I. | 0.0 | 1.0 | 1.5 | 3.0 | 1.5 |
| 5. W.O. Cy.Feed | 10.43 | - | 0.70 | - | 20.81 | 4.0 | % Weight | 0.0 | 31.41 | 48.58 | 13.55 | 6.46 |
| | | | | | | | % Ash | - | 24.69 | 19.43 | 18.76 | 21.03 |
| | | | | | | | F.S.I. | - | 3.5 | 5.0 | 4.5 | 2.0 |
| 6. W.O. Cy. Product | 6.01 | - | 0.99 | - | 15.04 | 4.0 | % Weight | 0.0 | 13.21 | 55.81 | 18.93 | 12.05 |
| | | | | | | | % Ash | - | 10.90 | 14.27 | 17.32 | 20.43 |
| | | | | | | | F.S.I. | - | 5.0 | 4.5 | 4.0 | 1.5 |
| 7. W.O. Cy. Reject | 85.24 | - | 0.87 | - | 42.76 | 1.0 | % Weight | 0.0 | 55.77 | 39.40 | 3.48 | 1.35 |
| | | | | | | | % Ash | - | 38.56 | 48.68 | 48.38 | 40.63 |
| | | | | | | | F.S.I. | - | 1.0 | 1.0 | 1.5 | 1.5 |
| 8. Sec.W.O. Cy.Product | 1.18 | - | 0.93 | - | 18.98 | 3.0 | % Weight | 0.0 | 8.50 | 54.35 | 15.10 | 22.05 |
| | | | | | | | % Ash | - | 13.29 | 19.85 | 22.93 | 16.35 |
| | | | | | | | F.S.I. | - | 4.0 | 2.0 | 1.0 | 1.0 |

| Sample | % Solids | % Air dry loss | % Res. Moist. | % Total Moist. | % Ash | F.S.I. | | + 1/4" | 1/4" x 28m | 28m x 100m | 100m x 200m | 200m x 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 9. Sec.W.O. Cy.Reject | 67.40 | - | 0.88 | - | 46.13 | 1.0 | % Weight | 0.0 | 63.72 | 34.16 | 1.89 | 0.23 |
| | | | | | | | % Ash | - | 38.44 | 59.74 | 73.85 | 63.18 |
| | | | | | | | F.S.I. | - | 1.0 | 1.0 | 0.5 | 0.5 |
| 10.S.B. Feed | 9.29 | - | 1.07 | - | 14.72 | 5.5 | % Weight | 0.0 | 23.33 | 55.75 | 15.06 | 5.86 |
| | | | | | | | % Ash | - | 10.57 | 14.67 | 17.22 | 19.69 |
| | | | | | | | F.S.I. | - | 5.0 | 5.5 | 3.5 | 2.0 |
| 11.S.B. Oversize | 25.08 | - | 0.88 | - | 13.12 | 5.0 | % Weight | 0.0 | 30.91 | 57.55 | 7.80 | 3.74 |
| | | | | | | | % Ash | - | 10.55 | 13.47 | 15.96 | 17.29 |
| | | | | | | | F.S.I. | - | 5.5 | 5.5 | 4.5 | 3.5 |
| 12.Flotation Feed | 4.82 | - | 0.97 | - | 15.40 | 4.5 | % Weight | 0.0 | 6.55 | 52.35 | 25.40 | 15.70 |
| | | | | | | | % Ash | - | 10.00 | 13.72 | 17.20 | 20.72 |
| | | | | | | | F.S.I. | - | 5.5 | 4.5 | 4.0 | 1.0 |
| Flotation 13.Product | 28.11 | - | 0.77 | - | 8.65 | 7.5 | % Weight | 0.0 | 3.84 | 37.93 | 34.60 | 23.63 |
| | | | | | | | % Ash | - | 6.73 | 7.99 | 8.94 | 9.78 |
| | | | | | | | F.S.I. | - | 9.0 | 9.0 | 9.0 | 5.5 |
| Flotation 14.Product | 2.31 | - | 0.87 | - | 26.17 | 2.0 | % Weight | 0.0 | 11.95 | 67.53 | 3.85 | 16.67 |
| | | | | | | | % Ash | - | 13.69 | 24.57 | 36.31 | 37.14 |
| | | | | | | | F.S.I. | - | 4.0 | 2.5 | 0.5 | 0.5 |
| 15.Fines Product | - | 12.07 | 1.11 | 13.18 | 9.98 | 8.0 | % Weight | 0.0 | 12.29 | 48.80 | 25.86 | 13.05 |
| | | | | | | | % Ash | - | 8.34 | 10.11 | 9.80 | 10.96 |
| | | | | | | | F.S.I. | - | 8.5 | 8.0 | 8.5 | 6.5 |
| 16.Plant Product | - | 5.78 | 0.68 | 6.46 | 11.99 | 6.0 | % Weight | 21.39 | 42.95 | 23.57 | 7.26 | 4.83 |
| | | | | | | | % Ash | 13.59 | 10.99 | 11.35 | 9.72 | 11.12 |
| | | | | | | | F.S.I. | 3.5 | 7.0 | 8.0 | 8.5 | 6.5 |

NOTE: All Ash results calculated to dry basis

| Sample | % Solids | % Air dry loss | % Res. Moist. | % Total Moist. | % Ash | F.S.I. | | + 1/4" | 1/4" x 28m | 28m x 100m | 100m x 200m | 200m x 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. Plant Feed | - | 3.50 | 1.01 | 4.51 | 22.17 | 5.0 | % Weight | 31.62 | 45.75 | 16.23 | 5.18 | 1.22 |
| | | | | | | | % Ash | 30.39 | 21.04 | 16.72 | 16.46 | 18.26 |
| | | | | | | | F.S.I. | 1.5 | 5.5 | 8.5 | 8.0 | 6.0 |
| 2. H.M. Feed | - | - | 0.79 | - | 23.47 | 3.0 | % Weight | 44.38 | 51.11 | 4.10 | 0.29 | 0.12 |
| | | | | | | | % Ash | 25.15 | 21.67 | 17.83 | 13.45 | 16.39 |
| | | | | | | | F.S.I. | 2.0 | 4.0 | 7.0 | 6.0 | 8.0 |
| 3. H.M. Product | - | - | 0.88 | - | 12.97 | 6.0 | % Weight | 34.42 | 63.47 | 1.78 | 0.21 | 0.12 |
| | | | | | | | % Ash | 13.88 | 12.22 | 10.18 | 9.08 | 12.54 |
| | | | | | | | F.S.I. | 4.5 | 6.5 | 7.5 | 7.5 | 8.0 |
| 4. H.M. Reject | - | - | 0.97 | - | 45.07 | 1.0 | % Weight | 35.82 | 62.62 | 1.07 | 0.19 | 0.30 |
| | | | | | | | % Ash | 43.26 | 41.99 | 38.23 | 28.30 | 28.57 |
| | | | | | | | F.S.I. | 1.0 | 1.0 | 1.5 | 4.0 | 2.5 |
| 5. W.O. Cy.Feed | 13.26 | - | 0.79 | - | 18.62 | 8.0 | % Weight | 0.0 | 27.37 | 45.63 | 15.94 | 11.06 |
| | | | | | | | % Ash | - | 20.18 | 17.85 | 16.83 | 19.69 |
| | | | | | | | F.S.I. | - | 6.0 | 8.0 | 6.5 | 6.0 |
| 6. W.O. Cy. Product | 6.57 | - | 0.95 | - | 15.34 | 8.0 | % Weight | 0.0 | 15.41 | 59.05 | 19.55 | 5.99 |
| | | | | | | | % Ash | - | 11.47 | 14.93 | 18.36 | 19.66 |
| | | | | | | | F.S.I. | - | 8.0 | 7.5 | 8.0 | 6.0 |
| 7. W.O. Cy. Reject | 61.41 | - | 0.94 | - | 39.66 | 1.0 | % Weight | 0.0 | 53.79 | 40.19 | 4.48 | 1.54 |
| | | | | | | | % Ash | - | 35.15 | 47.14 | 46.68 | 37.29 |
| | | | | | | | F.S.I. | - | 1.0 | 1.0 | 3.0 | 3.0 |
| 8. Sec.W.O. Cy.Product | 1.17 | - | 0.97 | - | 23.00 | 4.0 | % Weight | 0.0 | 26.94 | 56.34 | 12.04 | 4.68 |
| | | | | | | | % Ash | - | 15.87 | 24.20 | 32.55 | 24.07 |
| | | | | | | | F.S.I. | - | 5.5 | 5.5 | 4.5 | 4.0 |

| Sample | % Solids | % Air dry loss | % Res. Moist. | % Total Moist. | % Ash | F.S.I. | | + 1/4" | 1/4" x 28m | 28m x 100m | 100m x 200m | 200m x 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 9. Sec.W.O. Cy.Reject | 60.18 | - | 0.87 | - | 47.11 | 1.0 | % Weight | 0.00 | 65.31 | 32.99 | 1.50 | 0.20 |
| | | | | | | | % Ash | - | 37.95 | 59.27 | 75.32 | 54.82 |
| | | | | | | | F.S.I. | - | 1.0 | 1.0 | 1.0 | 1.0 |
| 10.S.B. Feed | 9.55 | - | 0.75 | - | 14.82 | 7.5 | % Weight | 0.0 | 22.98 | 53.99 | 12.67 | 10.36 |
| | | | | | | | % Ash | - | 11.31 | 15.51 | 17.04 | 17.84 |
| | | | | | | | F.S.I. | - | 7.5 | 7.5 | 7.5 | 7.5 |
| 11.S.B. Oversize | 44.56 | - | 0.80 | - | 12.21 | 8.0 | % Weight | 0.0 | 44.30 | 52.59 | 1.85 | 1.26 |
| | | | | | | | % Ash | - | 10.77 | 13.07 | 14.47 | 14.77 |
| | | | | | | | F.S.I. | - | 9.0 | 8.0 | 8.0 | 8.0 |
| 12.Flotation Feed | 4.55 | - | 0.97 | - | 16.62 | 8.0 | % Weight | 0.0 | 0.44 | 42.93 | 30.08 | 26.55 |
| | | | | | | | % Ash | - | I.S. | 14.38 | 16.24 | 19.53 |
| | | | | | | | F.S.I. | - | I.S. | 8.5 | 7.5 | 7.0 |
| 13.Flotation Product | 26.0 | - | 0.85 | - | 7.63 | 9.0 | % Weight | 0.0 | 0.32 | 43.72 | 37.96 | 18.00 |
| | | | | | | | % Ash | - | 11.13 | 6.86 | 7.90 | 8.89 |
| | | | | | | | F.S.I. | - | 8.0 | 9.0 | 9.0 | 8.5 |
| 14.Flotation Product | 3.57 | - | 1.03 | - | 21.89 | 5.5 | % Weight | 0.0 | 0.66 | 51.10 | 27.52 | 20.72 |
| | | | | | | | % Ash | - | 21.39 | 19.47 | 22.31 | 26.71 |
| | | | | | | | F.S.I. | - | 6.0 | 6.5 | 4.5 | 3.0 |
| 15.Fines Product | - | 13.03 | 0.79 | 13.82 | 10.60 | 8.5 | % Weight | 0.0 | 16.62 | 52.12 | 26.10 | 5.16 |
| | | | | | | | % Ash | - | 10.77 | 11.60 | 8.82 | 9.58 |
| | | | | | | | F.S.I. | - | 8.0 | 8.0 | 9.0 | 8.5 |
| 16.Plant Product | - | 3.09 | 0.70 | 3.79 | 12.55 | 7.0 | % Weight | 20.71 | 50.32 | 18.00 | 8.40 | 2.57 |
| | | | | | | | % Ash | 14.58 | 12.51 | 11.34 | 9.08 | 9.85 |
| | | | | | | | F.S.I. | 3.0 | 7.0 | 7.5 | 8.5 | 8.0 |

NOTE: All Ash results calculated to dry basis

# 8. APPENDIX 2

## 8.1 SOURCE CODE LISTING OF THE MONTE CARLO SIMULATION PROGRAM TO SIMULATE HEAVY MEDIA CYCLONE SAMPLING

```
C  PURPOSE: THE MONTE CARLO TECHNIQUE IS USED TO SIMULATE
C           100 REPETITIONS OF THE PLANT SAMPLING CAMPAINGS,
C           ASSUMING 5% RELATIVE ERROR ON ALL ASH MEASUREMENTS.
C
C
      DIMENSION Y7(100),Y8(100),Y9(100),YB(100),YA(100)
      DATA AY7/0./,AY8/0./,AY9/0./,AYB/0./,AYA/0./
      DIMENSION AA7(3),AA8(3),AA9(3),AAB(3),AAA(3)
      DATA AA7/0.,0.,0./,AA8/0.,0.,0./,AA9/0.,0.,0./,
     1AAB/0.,0.,0./,AAA/0.,0.,0./
C
      DIMENSION A7P(3),A8P(3),A9P(3),ABP(3),AAP(3)
      DIMENSION A7(3),A8(3),A9(3),AB(3),AA(3)
      DATA A7/40.28,61.54,11.15/,A8/19.59,42.54,7.84/,
     1A9/25.58,71.13,8.94/,AB/32.21,67.64,11.47/,
     1AA/23.47,45.07,12.97/
      DIMENSION SD7(3),SD8(3),SD9(3),SDB(3),SDA(3)
C
C
      DO 10 I=1,3
      SD7(I)=(A7(I)*.05)/10.**.5
      SD8(I)=(A8(I)*.05)/10.**.5
      SD9(I)=(A9(I)*.05)/10.**.5
      SDB(I)=(AB(I)*.05)/10.**.5
      SDA(I)=(AA(I)*.05)/10.**.5
 10   CONTINUE
C
      DO 30 K=1,100
      DO 20 J=1,3
C   FOR SEAM #7
      CALL NOISE(A7(J),SD7(J),A7P(J))
C   FOR SEAM #8
      CALL NOISE(A8(J),SD8(J),A8P(J))
C   FOR SEAM #9
      CALL NOISE(A9(J),SD9(J),A9P(J))
C   FOR SEAM #10B
      CALL NOISE(AB(J),SDB(J),ABP(J))
C   FOR SEAM #10A
      CALL NOISE(AA(J),SDA(J),AAP(J))
C
      AA7(J)=AA7(J)+A7P(J)
      AA8(J)=AA8(J)+A8P(J)
      AA9(J)=AA9(J)+A9P(J)
      AAB(J)=AAB(J)+ABP(J)
      AAA(J)=AAA(J)+AAP(J)
 20   CONTINUE
C
      Y7(K)=(A7P(1)-A7P(2))/(A7P(3)-A7P(2))
      Y8(K)=(A8P(1)-A8P(2))/(A8P(3)-A8P(2))
      Y9(K)=(A9P(1)-A9P(2))/(A9P(3)-A9P(2))
      YB(K)=(ABP(1)-ABP(2))/(ABP(3)-ABP(2))
      YA(K)=(AAP(1)-AAP(2))/(AAP(3)-AAP(2))
C
      AY7=AY7+Y7(K)
      AY8=AY8+Y8(K)
      AY9=AY9+Y9(K)
      AYB=AYB+YB(K)
      AYA=AYA+YA(K)
 30   CONTINUE
C
```

```
      AY7=AY7/K
      AY8=AY8/K
      AY9=AY9/K
      AYB=AYB/K
      AYA=AYA/K
C
      DO 50 L=1,3
      AA7(L)=AA7(L)/K
      AA8(L)=AA8(L)/K
      AA9(L)=AA9(L)/K
      AAB(L)=AAB(L)/K
      AAA(L)=AAA(L)/K
 50   CONTINUE
C
      STD7=0.
      STD8=0.
      STD9=0.
      STDB=0.
      STDA=0.
C
      DO 60 M=1,100
      STD7=STD7+(Y7(M)-AY7)**2.
      STD8=STD8+(Y8(M)-AY8)**2.
      STD9=STD9+(Y9(M)-AY9)**2.
      STDB=STDB+(YB(M)-AYB)**2.
      STDA=STDA+(YA(M)-AYA)**2.
 60   CONTINUE
C
      STD7=(STD7/M)**.5
      STD8=(STD8/M)**.5
      STD9=(STD9/M)**.5
      STDB=(STDB/M)**.5
      STDA=(STDA/M)**.5
C
      WRITE(*,70)
 70   FORMAT(5X,34HSEAM (%ASH)   FEED   TAIL.   CONC.)
      WRITE(*,80)(AA7(1),AA7(2),AA7(3))
 80   FORMAT(6X,3H#7 ,6X,3F8.2)
      WRITE(*,90)(AA8(1),AA8(2),AA8(3))
 90   FORMAT(6X,3H#8 ,6X,3F8.2)
      WRITE(*,100)(AA9(1),AA9(2),AA9(3))
 100  FORMAT(6X,3H#9 ,6X,3F8.2)
      WRITE(*,110)(AAB(1),AAB(2),AAB(3))
 110  FORMAT(6X,5H#10B ,4X,3F8.2)
      WRITE(*,120)(AAA(1),AAA(2),AAA(3))
 120  FORMAT(6X,5H#10A ,4X,3F8.2)
C
      WRITE(*,130)
 130  FORMAT(5X,32HSEAM      MEAN YIELD   STD. DEV. )
      WRITE(*,140)AY7,STD7
 140  FORMAT(6X,3H#7 ,5X,2F11.4)
      WRITE(*,150)AY8,STD8
 150  FORMAT(6X,3H#8 ,5X,2F11.4)
      WRITE(*,160)AY9,STD9
 160  FORMAT(6X,3H#9 ,5X,2F11.4)
      WRITE(*,170)AYB,STDB
 170  FORMAT(6X,5H#10B ,3X,2F11.4)
      WRITE(*,180)AYA,STDA
 180  FORMAT(6X,5H#10A ,3X,2F11.4)
      STOP
```

```
      END
C
C     SUBROUTINE NOISE
C
      SUBROUTINE NOISE(INPUT,STDDEV,OUTPUT)
C
      DIMENSION R(2)
      REAL INPUT
      DATA ISEED/428956419/,PI/3.1415927/,IFLAG/1/,LA/16807/
      DATA LB15/32768/,LB16/65536/,LP/2147483647/
C
C     DETERMINE WHETHER THE RANDOM NORMAL DEVIATES NEED
C     TO BE REFRESHED
C
      IF(IFLAG.EQ.1)GO TO 15
      RR=R(2)
      Z=Z2
      IFLAG=1
      GO TO 25
C
C     GENERATE TWO UNIFORM RANDOM DEVIATES IN R
C
 15   DO 35 KK=1,2
      LHI=ISEED/LB16
      LALO=(ISEED-LHI*LB16)*LA
      LEFTLO=LALO/LB16
      LFHI=LHI*LA+LEFTLO
      K=LFHI/LB15
      ISEED=(((LALO-LEFTLO*LB16)-LP)+(LFHI-K*LB15)*LB16)+K
      IF(ISEED.LT.0)ISEED=ISEED+LP
      R(KK)=FLOAT(ISEED)*4.656612875E-10
 35   CONTINUE
C
C     GENERATE TWO NORMAL RANDOM DEVIATES WITH N(Z;0,1)
C
      Z=(-2.*ALOG(R(1)))**.5*COS(2.*PI*R(2))
      Z2=(-2.*ALOG(R(1)))**.5*SIN(2.*PI*R(2))
      RR=R(1)
      IFLAG=2
C
C     CALCULATE THE STOCHASTIC OUTPUT SIGNAL
C
 25   OUTPUT=INPUT+Z*STDDEV
C
C     LOCAL PROCESSING IS COMPLETE
C
 9999 RETURN
      END
```

# 9. APPENDIX 3

## 9.1 SAMPLE CALCULATION OF DISTRIBUTION MODULUS AT DIFFERENT LEVELS OF CLEAN COAL ASH FOR NUMBER 8 SEAM

From base case washability data:

| $A_o$ | Y |
|---|---|
| 7 | 0.663 |
| 8 | 0.733 |
| 9 | 0.780 |
| 10 | 0.815 |

Rearranging equation 4.1:

$$\alpha = \frac{\log Y}{\log \left(\frac{A_o - A_i}{A_r - A_i}\right)}$$

Therefore for; $A_o = 7$ , $\alpha = 0.3153$

$A_o = 8$ , $\alpha = 0.2771$

$A_o = 9$ , $\alpha = 0.2569$

$A_o = 10$ , $\alpha = 0.2453$

This, along with the data for the other seams are plotted in figure 9.1.

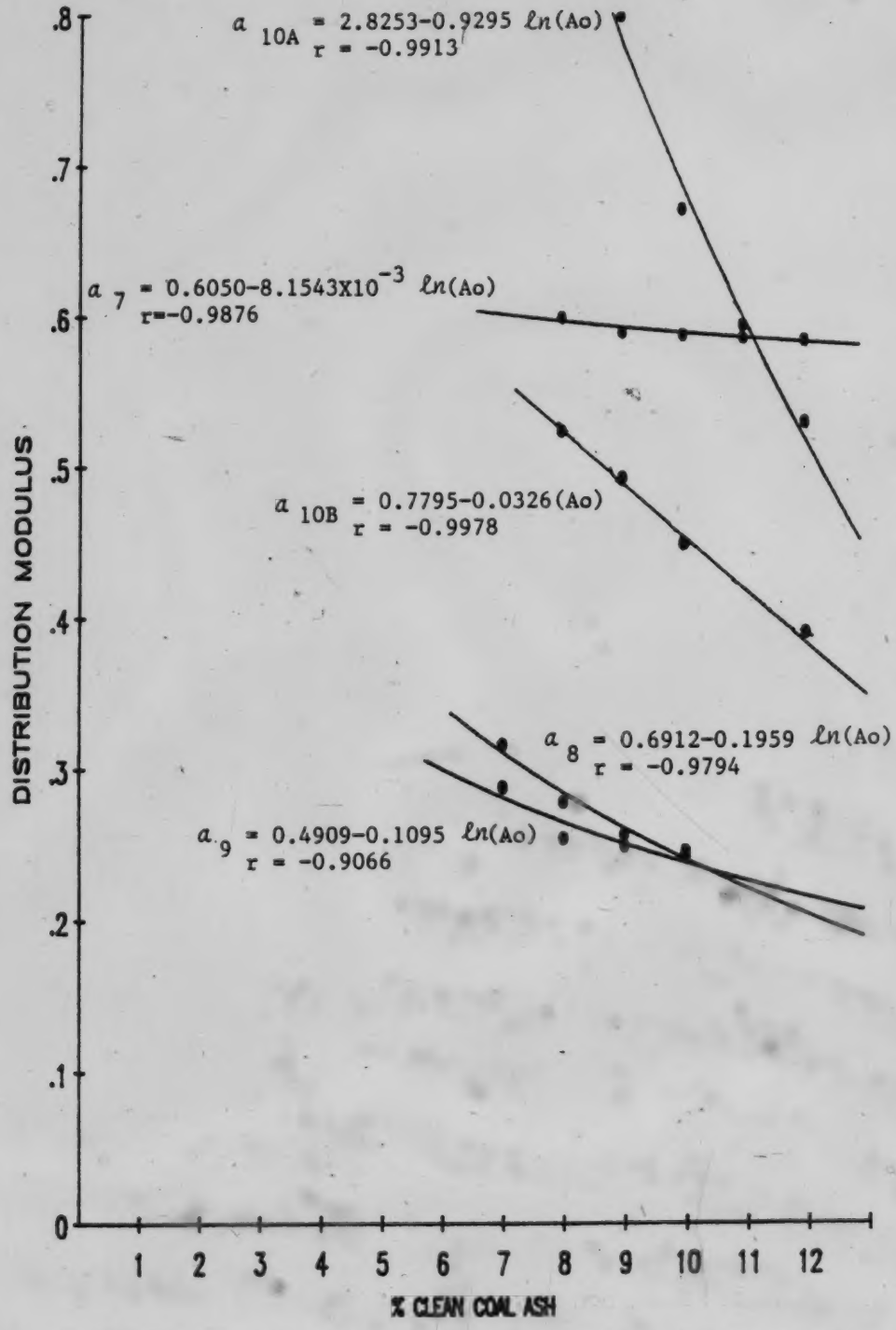



Figure 9.1 Change in Distribution Modulus ($a$) With Clean Coal Ash

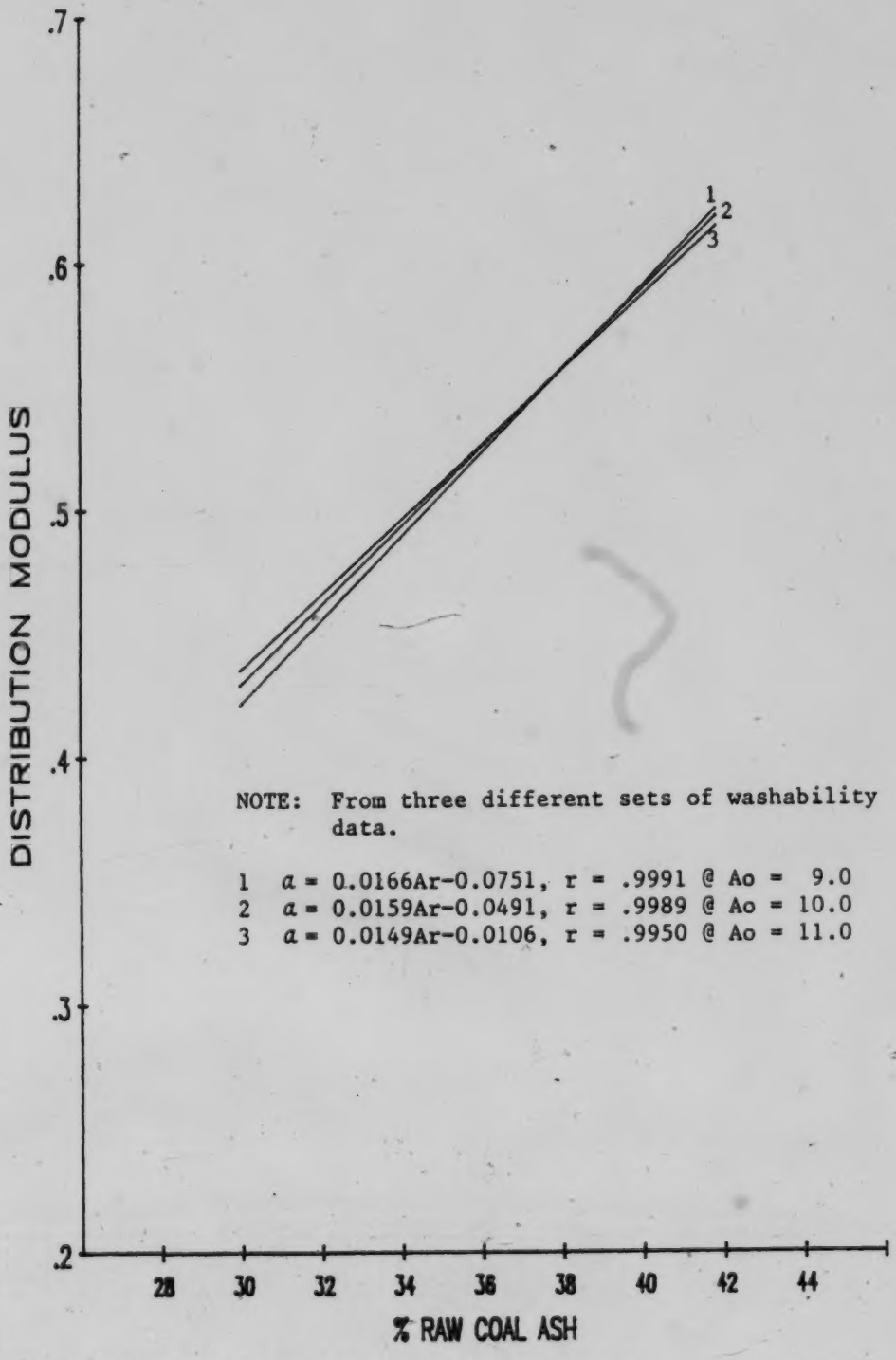
# 10. APPENDIX 4

## 10.1 SAMPLE CALCULATION OF DISTRIBUTION MODULUS AT DIFFERENT LEVELS OF RAW COAL ASH FOR NUMBER 8 SEAM

If $A_o$ is taken to be 9.0, the following is obtained from four different sets of washability data for #8 seam:

| | $A_r$ | $A_o$ | Y | therefore since $\alpha = \frac{\log Y}{\log \left(\frac{A_o - A_1}{A_r - A_1}\right)}$, | $\alpha$ |
|---|---|---|---|---|---|
| 1 | 23.57 | 9.0 | 0.63 | | 0.4106 |
| 2 | 19.26 | 9.0 | 0.72 | | 0.3640 |
| 3 | 14.5 | 9.0 | 0.868 | | 0.2442 |
| 4 | 18.7 | 9.0 | 0.75 | | 0.3309 |

The procedure can be repeated at different levels of $A_o$. The plotted results for #8 seam are given in figure 4.3 and for the other seams the plotted results are given in the remainder of Appendix 4.




NOTE: From three different sets of washability data.

1 $\alpha$ = 0.0166Ar-0.0751, r = .9991 @ Ao = 9.0
2 $\alpha$ = 0.0159Ar-0.0491, r = .9989 @ Ao = 10.0
3 $\alpha$ = 0.0149Ar-0.0106, r = .9950 @ Ao = 11.0

Figure 10.1 Change in Distribution Modulus With Raw Coal Ash For #7 Seam

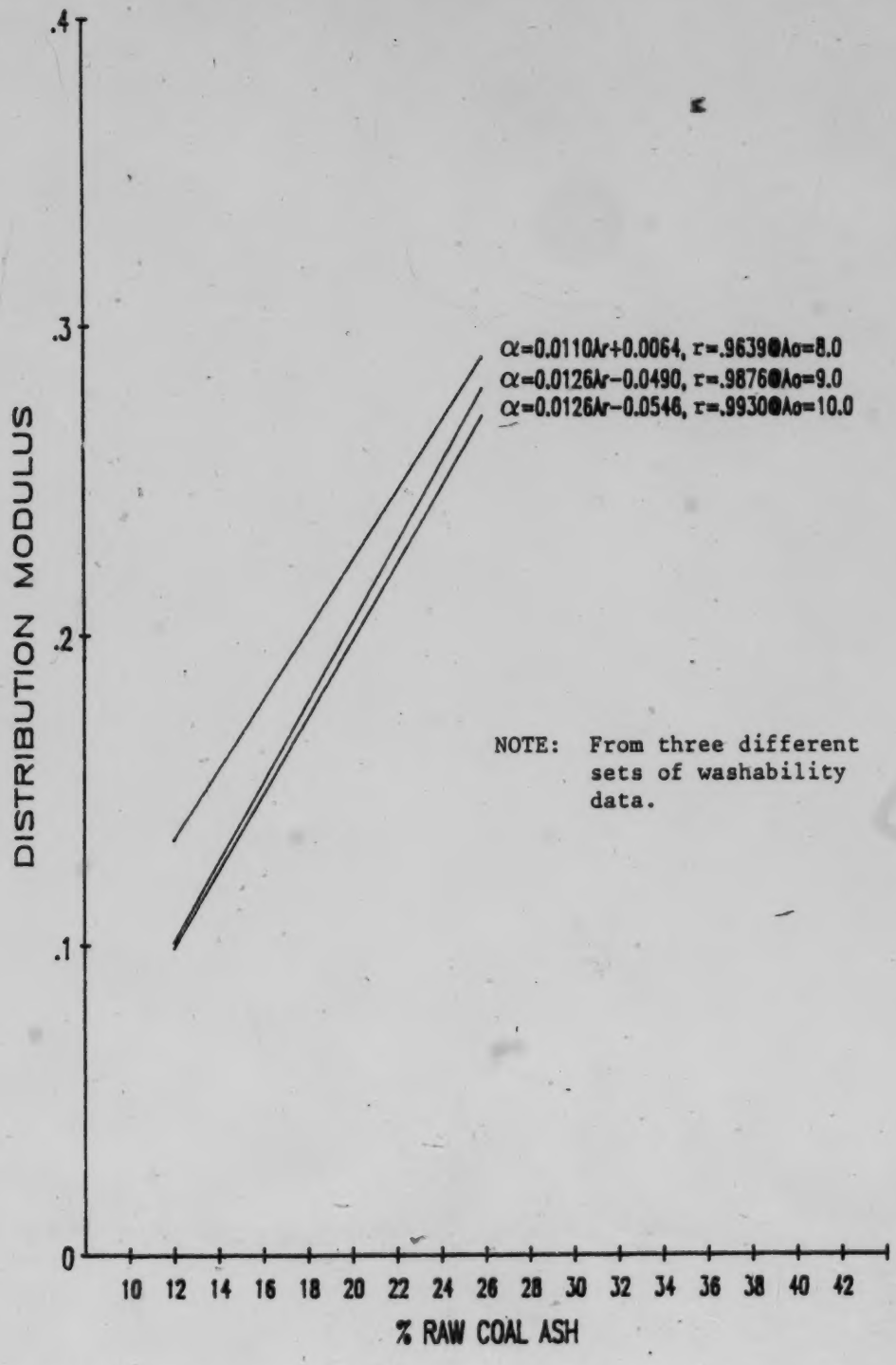



Figure 10.2 Change in Distribution Modulus With Raw Coal Ash For #9 Seam

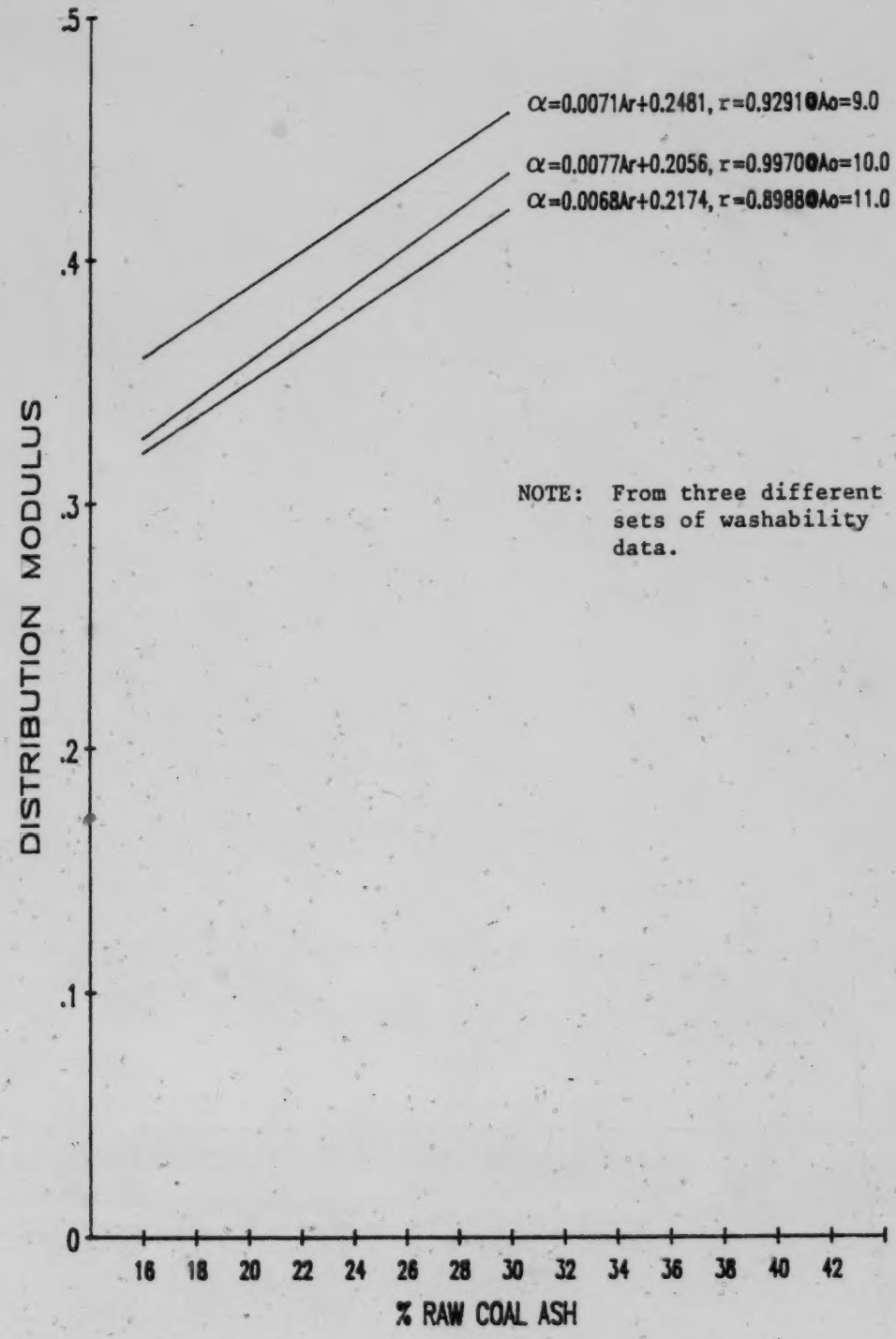



Figure 10.3 Change in Distribution Modulus With Raw Coal Ash For #10B Seam

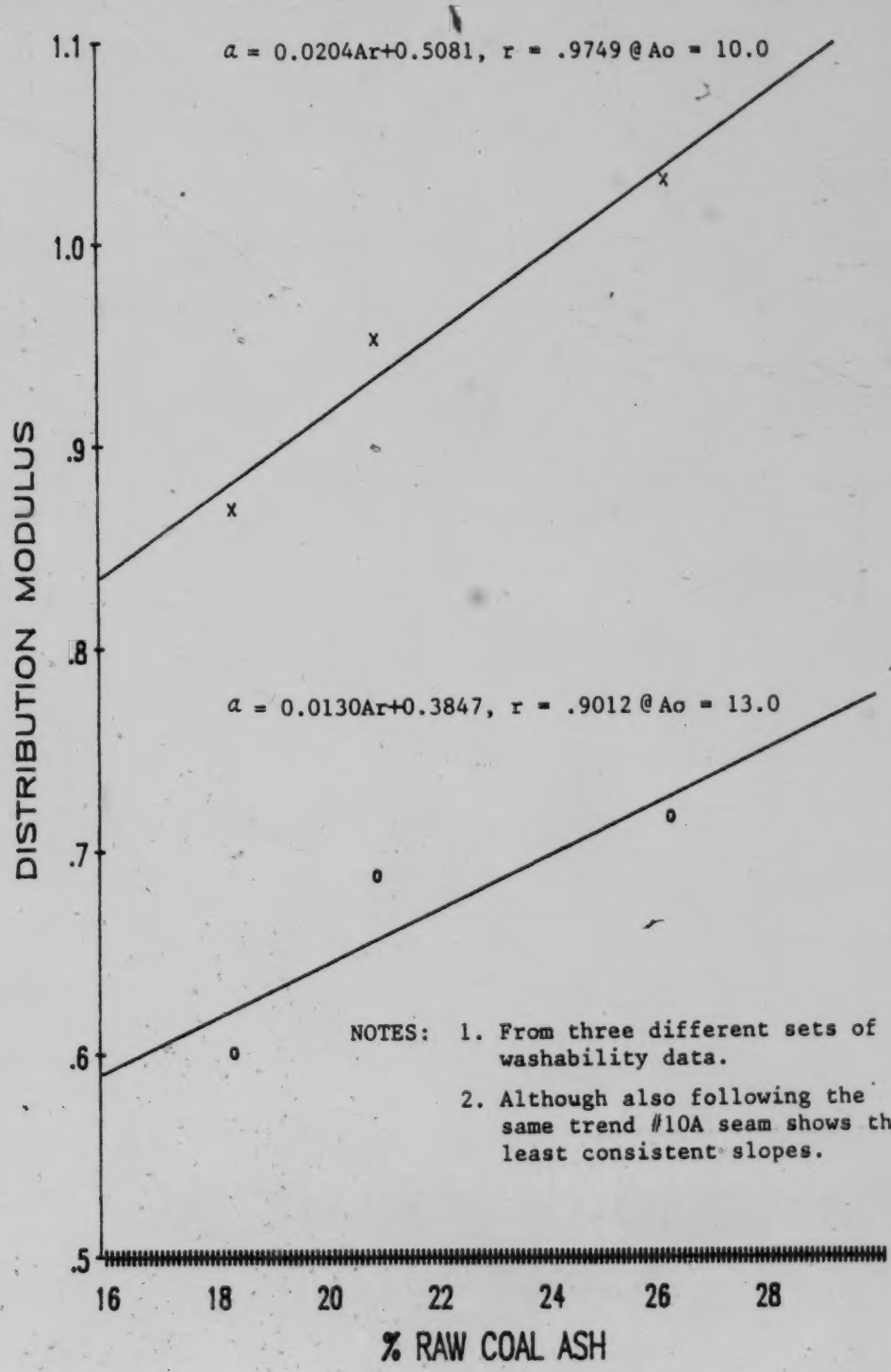



Figure 10.4 Change in Distribution Modulus With Raw Coal Ash For #10A Seam

## 11. APPENDIX 5

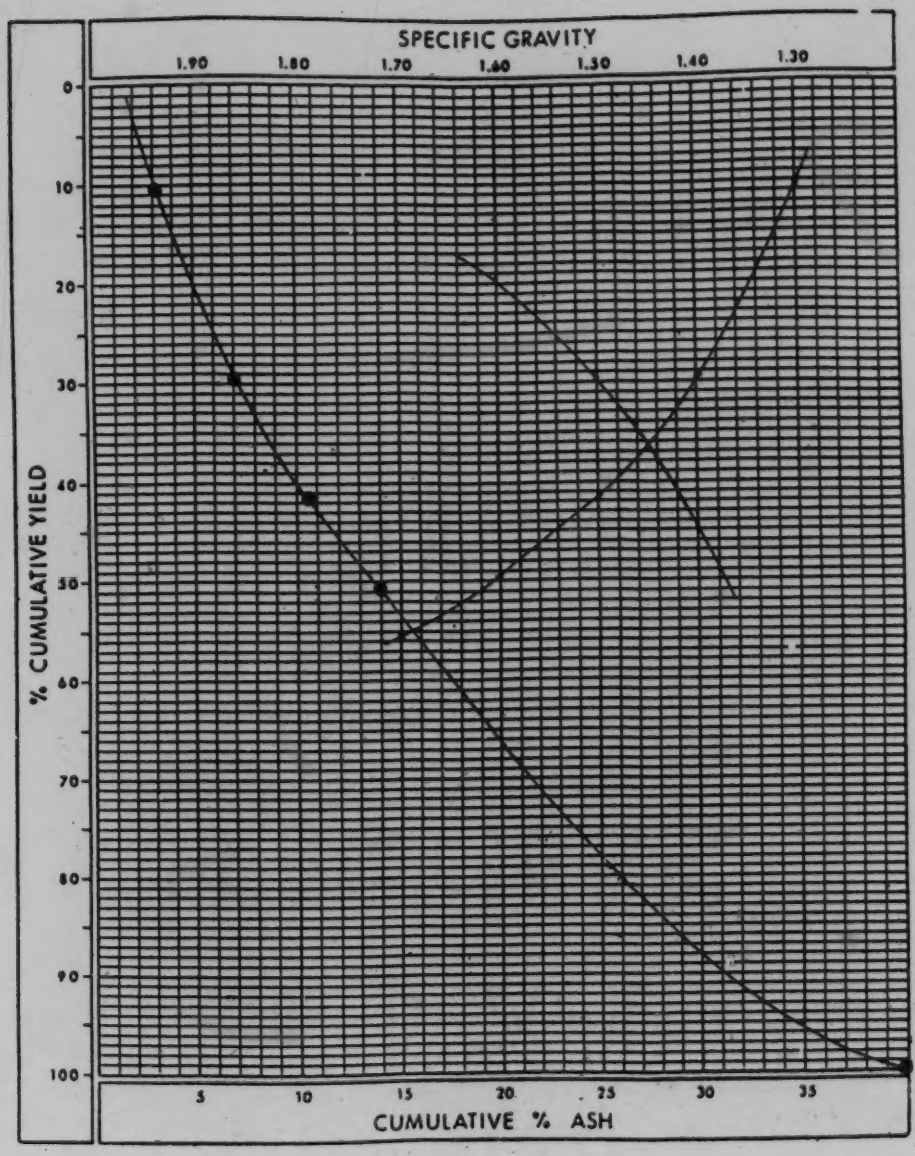



Figure 11.1 Washability Curves for #7 Seam

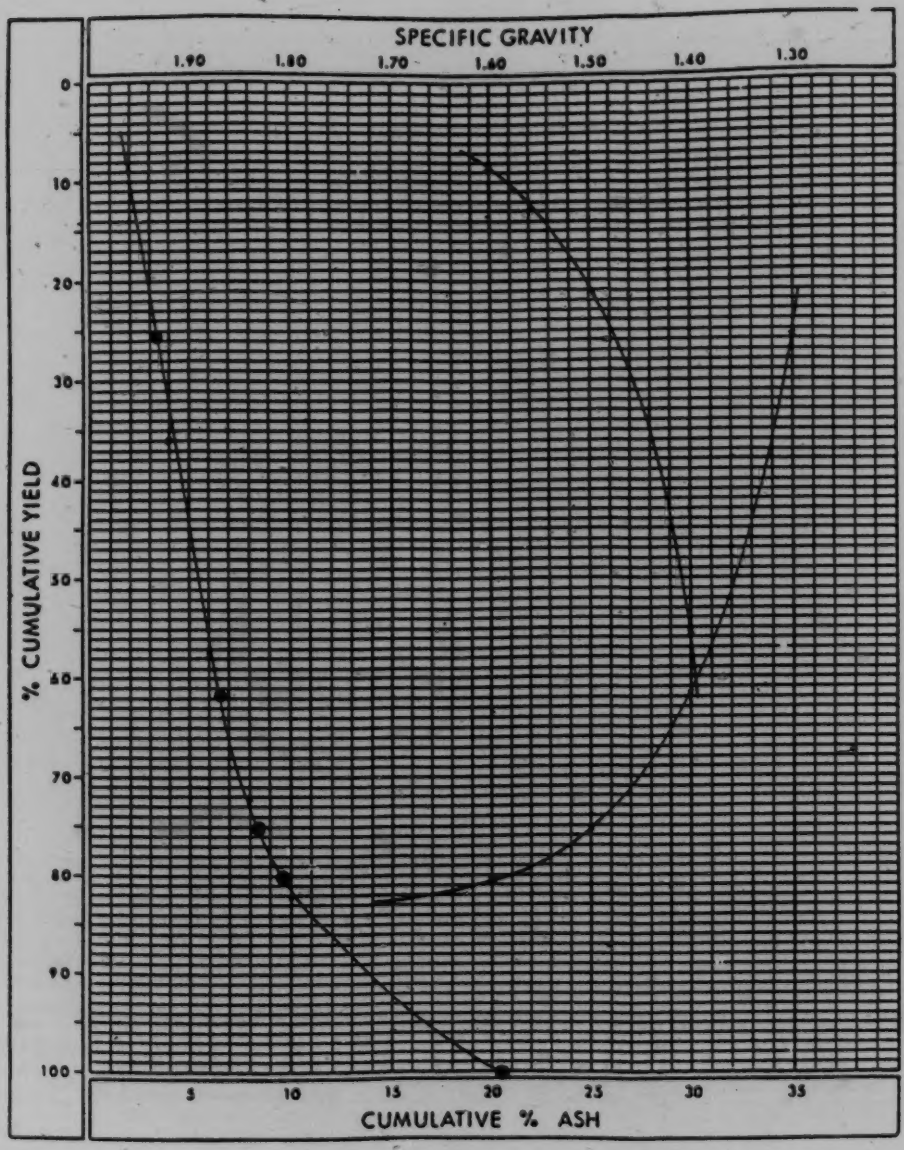



Figure 11.2 Washability Curves for #8 Seam

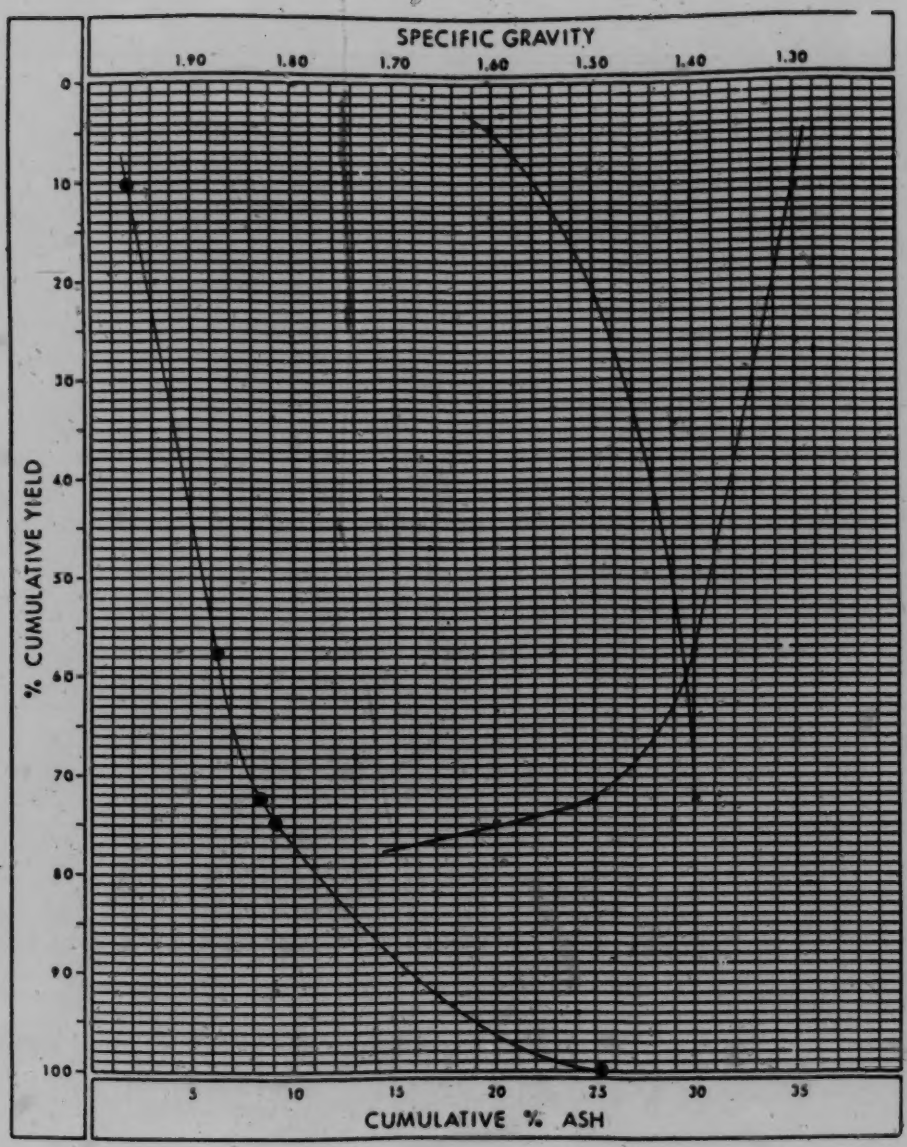



Figure 11.3 Washability Curves for #9 Seam

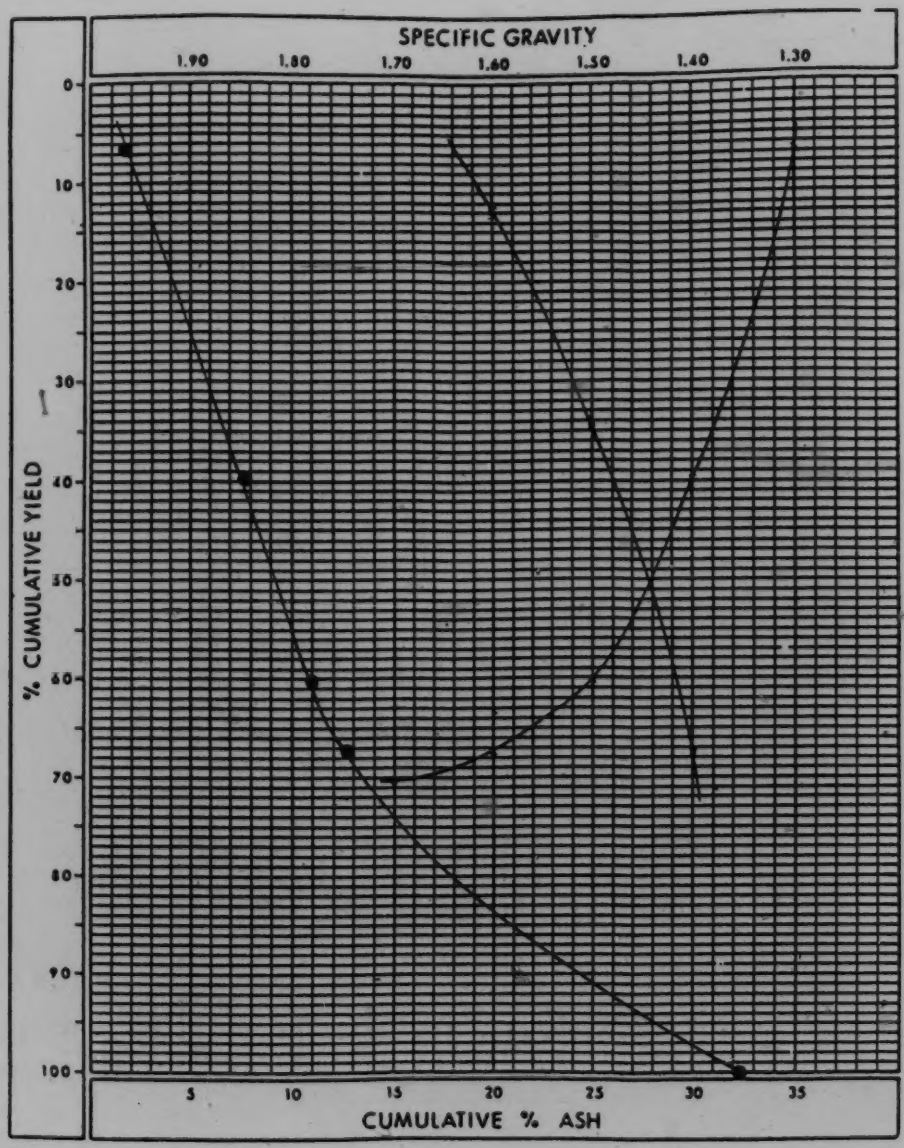



Figure 11.4 Washability Curves for #10B Seam

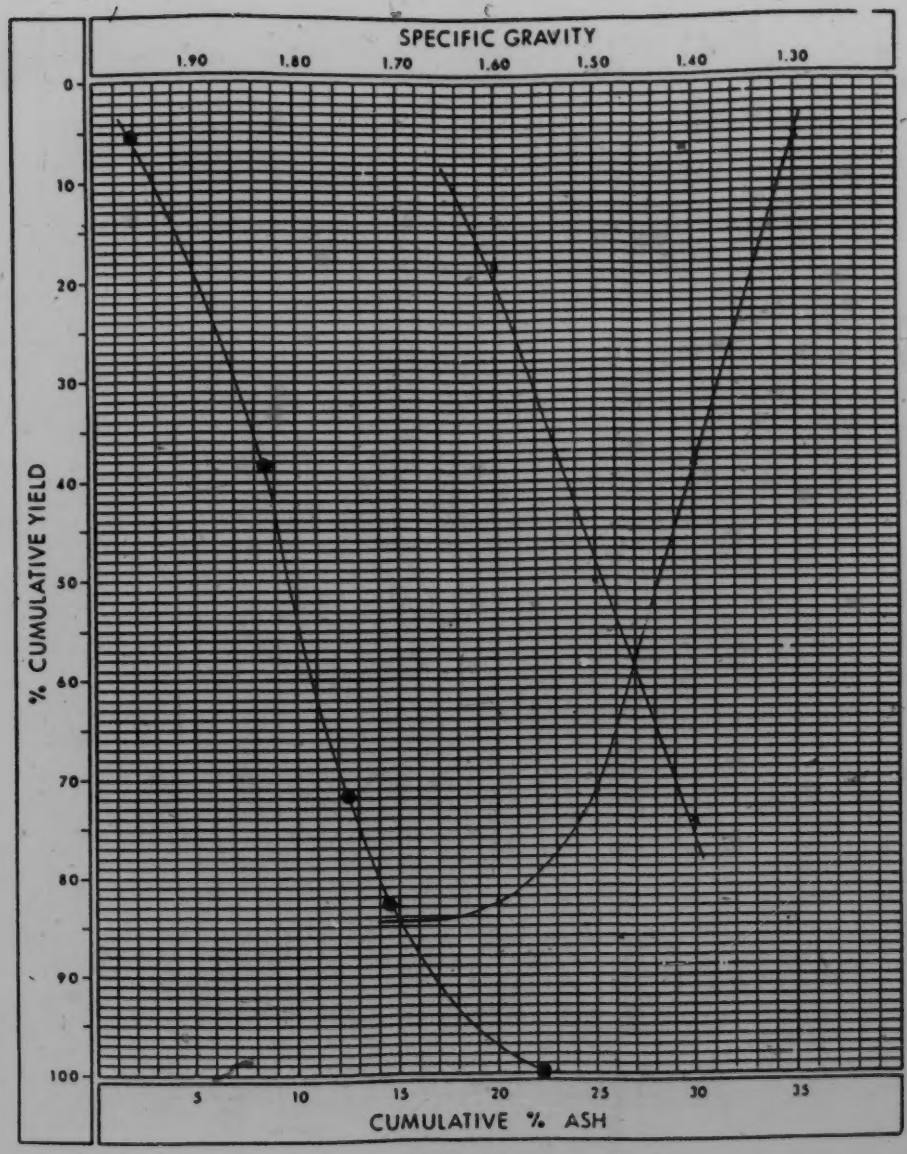



Figure 11.5 Washability Curves for #10A Seam

# 12. APPENDIX 6

## 12.1 SAMPLE CALCULATION OF CLEAN COAL ASH AND YIELD VALUES AT DIFFERENT CUTPOINTS FOR NUMBER 8 SEAM

Note: the generalized distribution curve, given in figure 2.2 and generated from the reduced distribution data of the five Plant Trials, is used to calculate all results.

| $D_{50}$ Mean S.G. | % Wt. of Feed | % Ash | X | D.F. | D.F.x % Wt. | %A x D.F. x %Wt. Yield |
|---|---|---|---|---|---|---|
| 1.40 1.25 | 25.62 | 3.37 | 0.893 | 0.991 | 25.389 | 1.489 |
| 1.35 | 36.19 | 8.88 | 0.964 | 0.820 | 29.676 | 4.586 |
| 1.45 | 13.27 | 16.98 | 1.036 | 0.150 | 1.991 | 0.588 |
| 1.55 | 5.02 | 26.11 | 1.107 | 0.030 | 0.151 | 0.069 |
| 2.20 | 19.90 | 64.15 | 1.571 | 0.013 | 0.259 | 0.289 |
| | | | | Yield = | 57.47 | $A_o$ = 7.02 |
| 1.43 Same | Same | Same | 0.874 | 0.993 | 25.441 | 1.329 |
| | | | 0.944 | 0.935 | 33.838 | 4.658 |
| | | | 1.014 | 0.360 | 4.777 | 1.257 |
| | | | 1.084 | 0.035 | 0.176 | 0.071 |
| | | | 1.538 | 0.014 | 0.279 | 0.277 |
| | | | | Yield = | 64.51 | $A_o$ = 7.59 |
| 1.50 Same | Same | Same | 0.833 | 0.994 | 25.466 | 1.170 |
| | | | 0.900 | 0.990 | 35.828 | 4.338 |
| | | | 0.967 | 0.819 | 10.868 | 2.516 |
| | | | 1.033 | 0.175 | 0.879 | 0.313 |
| | | | 1.467 | 0.015 | 0.299 | 0.262 |
| | | | | Yield = | 73.35 | $A_o$ = 8.60 |

| $D_{50}$ Mean S.G. | % Wt. of Feed | % Ash | X | D.F. | D.F.x % Wt. | %A x D.F. x %Wt. Yield |
|---|---|---|---|---|---|---|
| 1.60 | Same | Same | Same | 0.781 | 0.998 | 25.569 | 1.092 |
| | | | | 0.844 | 0.993 | 35.937 | 4.045 |
| | | | | 0.906 | 0.990 | 13.137 | 2.828 |
| | | | | 0.969 | 0.770 | 3.865 | 1.279 |
| | | | | 1.375 | 0.019 | 0.378 | 0.307 |
| | | | | | Yield = | 78.89 | $A_o$ = 9.55 |

# 13. APPENDIX 7

## 13.1 SOURCE LISTING OF THE PROGRAM TO CALCULATE YIELD AND CLEAN COAL ASH

```
      REAL*8 C7(11),C8(11),C9(11),C8(11),CA(11)
      dimension ao(21),hy(21),py(21),sgs(21),re(21)
      dimension o7(21),o8(21),o9(21),o10b(21),o10a(21)
      INTEGER S7T,S8T,S9T,S10BT,S10AT,S7,S8,S9,S10B,S10A,ST
C
C     DATA STATEMENT FOR SEAM 7 CONSTANTS
C
      DATA C7/14126.8423.,-4.111,25.6705,26.7116,0.6050,0.0081543,
     1  0.0155,39.99,.7466,0.2534,11.95/,FY7/0.4707/
C
C     DATA STATEMENT FOR SEAM 8 CONSTANTS
C
      DATA C8/28240884.76,-9.4097,12.4661,10.2905,0.6912,.1954,
     1  0.0188,20.41,.8022,.1978,8.22/,FY8/0.8227/
C
C     DATA STATEMENT FOR SEAM 9 CONSTANTS
C
      DATA C9/3114670796.,-12.5569,11.5630,8.9066,0.4909,0.1095,
     1  0.0126,25.21,.8191,0.1809,7.84/,FY9/.5040/
C
C     DATA STATEMENT FOR SEAM 10B CONSTANTS
C
      DATA CB/8012589.098,-8.306,18.23,16.137,0.7795,0.0326,0.007652,
     1  32.21,.7994,0.2006,9.98/,FY10B/0.5502/
C
C     DATA STATEMENT FOR SEAM 10A CONSTANTS
C
      DATA CA/1589736.361,-7.0469,21.624,20.0154,2.8253,0.9295,0.013,
     1  22.19,0.7417,0.2583,10.60/,FY10A/0.4954/
      write(*,10)
10    format(5x,12hRAW COAL ASH)
C
C     input data for seam ash
C
      write(*,20)
20    format(5x,43hSEAM;    #7      #8       #9      #10B      #10A)
      READ(*,30)AR7,AR8,AR9,AR10B,AR10A
30    FORMAT(5F6.1)
C
C     INPUT DATA FOR TONNES OF COAL AVAILABLE
C
      WRITE(*,40)
40    FORMAT(5X,45HTONNE OF;  #7      #8       #9      #10B      #10A)
      READ(*,50)S7T,S8T,S9T,S10BT,S10AT
50    FORMAT(5I6)
      IC=1
      ST=S7T+S8T+S9T+S10BT+S10AT
      DO 600 ISG=140,160
C
C     CALCULATE QUALITIES AND YIELDS
C
      SG=FLOAT(ISG)/100.
C
C     CALL QUALITY AND YIELD ROUTINE FOR #7
C
      IS=1
      CALL PERF(IS,S7T,AR7,SG,C7,AO7T,PY7,FY7,HY7,Y7)
C
C     CALL QUALITY AND YIELD ROUTINE FOR #8
C
      IS=2
      CALL PERF(IS,S8T,AR8,SG,C8,AO8T,PY8,FY8,HY8,Y8)
```

```
C
C       CALL QUALITY AND YIELD ROUTINE FOR #9 ---
C
        IS=3
        CALL PERF(IS,S9T,AR9,SG,C9,AD9T,PY9,FY9,HY9,Y9)
C
C       CALL QUALITY AND YIELD ROUTINE FOR #10B
C
        IS=4
        CALL PERF(IS,S10BT,AR10B,SG,CB,AD10BT,PY10B,FY10B,HY10B,Y10B)
C
C       CALL QUALITY AND YIELD ROUTINE FOR #10A
C
        IS=5
        CALL PERF(IS,S10AT,AR10A,SG,CA,AD10AT,PY10A,FY10A,HY10A,Y10A)
C
C
C
        AOT=(S7T*AD7T+S8T*AD8T+S9T*AD9T+S10BT*AD10BT+S10AT*AD10AT)/ST
        P7(IC)=(S7T*100.)/ST
        P8(IC)=(S8T*100.)/ST
        P9(IC)=(S9T*100.)/ST
        P10B(IC)=(S10BT*100.)/ST
        P10A(IC)=(S10AT*100.)/ST
        AO(IC)=AOT
C
C       CALCULATE TOTAL HEAVY MEDIA YIELD
C
        HY(IC)=HY7*P7(IC)+HY8*P8(IC)+HY9*P9(IC)+HY10B*P10B(IC)
     1  +HY10A*P10A(IC)
C
C       CALCULATE PLANT YIELD AND CORRECT FOR MOISTURE
C
        PYT=PY7*P7(IC)+PY8*P8(IC)+PY9*P9(IC)+PY10B*P10B(IC)+PY10A*P10A(IC)
        PY(IC)=PYT*1.038
        SGS(IC)=SG
        YT=Y7*P7(IC)+Y8*P8(IC)+Y9*P9(IC)+Y10B*P10B(IC)+Y10A*P10A(IC)
        RE(IC)=HY(IC)/YT
        IC=1+IC
600     CONTINUE
        IC=IC-1
625     CALL SORT(IC,PY,AO,P7,P8,P9,P10B,P10A,SGS,HY,RE)
        WRITE(*,650)
650     FORMAT(' ',' #7 #8 #9 #10B #10A SG CCx'
     1  '  HMX  YLD%  RE'/80('-'))
        WRITE(*,700) (P7(I),P8(I),P9(I),P10B(I),P10A(I),SGS(I),AO(I),
     1  HY(I),PY(I),RE(I),I=1,IC)
700     FORMAT(' ',2X,10F7.2)
        STOP
        END
C
C       SUBROUTINE PERF CALCULATES YIELD AND CLEAN COAL ASH FOR SEAMS
C
        SUBROUTINE PERF(IS,ITONNES,RASH,SG,C,AOT,PY,FY,HY,Y)
        REAL*8 C(11)
        REAL NG,HY
        IF (ITONNES.EQ.0) RETURN
        AR=RASH+1.7
        NG=C(1)*EXP(C(2)*SG)
        RE=EXP(-.0002*NG)-(NG/45.)*(NG/45.)*.1
        AO=C(3)*SG-C(4)
C       IF SEAM IS 10B GO TO 5
        IF (IS.EQ.4) GO TO 5
        DM=C(5)-C(6)*ALOG(AO)+C(7)*(AR-C(8))
        GO TO 10
5       DM=C(5)-C(6)*AO+C(7)*(AR-C(8))
```

```
10      Y=((AO-2.)/(AR-2.))**DM
        HY=Y*RE
        PY=HY*C(9)+FY*C(10)
        AOT=(AO*HY*C(9)+C(11)*FY*C(10))/PY
        RETURN
        END

C
C       SUBROUTINE SORT
C
        SUBROUTINE SORT(N,A,B,C,D,E,F,G,H,K,L)
        REAL*4 A(N),B(N),C(N),D(N),E(N),F(N),G(N),H(N),K(N),L(N)
50      DO 1500 J=1,N-1
        DO 1000 I=1,N-J
        IF (A(I).GE.A(I+1)) GO TO 1000
        STORE=A(I)
        A(I)=A(I+1)
        A(I+1)=STORE
        STORE=B(I)
        B(I)=B(I+1)
        B(I+1)=STORE
        STORE=C(I)
        C(I)=C(I+1)
        C(I+1)=STORE
        STORE=D(I)
        D(I)=D(I+1)
        D(I+1)=STORE
        STORE=E(I)
        E(I)=E(I+1)
        E(I+1)=STORE
        STORE=F(I)
        F(I)=F(I+1)
        F(I+1)=STORE
        STORE=G(I)
        G(I)=G(I+1)
        G(I+1)=STORE
        STORE=H(I)
        H(I)=H(I+1)
        H(I+1)=STORE
        STORE=K(I)
        K(I)=K(I+1)
        K(I+1)=STORE
        STORE=L(I)
        L(I)=L(I+1)
        L(I+1)=STORE
1000    CONTINUE
1500    CONTINUE
        RETURN
        END
```

## 13.2 SOURCE LISTING OF THE FEED OPTIMIZATION PROGRAM

```
      REAL*8 C7(11),C8(11),C9(11),C8(11),CA(11)
      DIMENSION AO(10),HY(10),PY(10),SGS(10),RE(10)
      DIMENSION P7(10),P8(10),P9(10),P10B(10),P10A(10)
      INTEGER S7T,S8T,S9T,S10BT,S10AT,S7,S8,S9,S10B,S10A,ST
C
C     DATA STATEMENT FOR SEAM 7 CONSTANTS
C
      DATA C7/14126.2423,-4.111,25.6705,26.7116,0.6050,0.0081543,
     1 0.0155,39.99,.7466,0.2534,11.95/,FY7/0.4707/
C
C     DATA STATEMENT FOR SEAM 8 CONSTANTS
C
      DATA C8/28240884.76,-9.4097,12.4661,10.2905,0.6912,.1954,
     1 0.0188,20.41,.8022,.1978,8.22/,FY8/0.8227/
C
C     DATA STATEMENT FOR SEAM 9 CONSTANTS
C
      DATA C9/3114670796.,-12.5569,11.5630,8.9066,0.4909,0.1095,
     1 0.0126,25.21,.8191,0.1809,7.84/,FY9/.5040/
C
C     DATA STATEMENT FOR SEAM 10B CONSTANTS
C
      DATA CB/8012589.098,-8.306,18.23,16.137,0.7795,0.0326,0.007652,
     1 32.21,.7994,0.2006,9.98/,FY10B/0.5502/
C
C     DATA STATEMENT FOR SEAM 10A CONSTANTS
C
      DATA CA/1589736.361,-7.0469,21.624,20.0154,2.8253,0.9295,0.013,
     1 22.19,0.7417,0.2583,10.60/,FY10A/0.4954/
      WRITE(*,10)
10    FORMAT(5x,12hRAW COAL ASH)
C
C     INPUT DATA FOR SEAM ASH
C
      WRITE(*,20)
20    FORMAT(5x,43hSEAM;    #7      #8       #9      #10B      #10A)
      READ(*,30)AR7,AR8,AR9,AR10B,AR10A
30    FORMAT(5F6.1)
C
C     INPUT DATA FOR TONNES OF COAL AVAILABLE
C
      WRITE(*,40)
40    FORMAT(5X,45HTONNE OF;  #7      #8       #9      #10B      #10A)
      READ(*,50)S7T,S8T,S9T,S10BT,S10AT
50    FORMAT(5I6)

C
C     ZERO ARRAYS
C
      DO 60 I=1,10
      AO(I)=0.0
      HY(I)=0.0
      PY(I)=0.0
      SGS(I)=0.0
      RE(I)=0.0
      P7(I)=0.0
      P8(I)=0.0
      P9(I)=0.0
      P10B(I)=0.0
      P10A(I)=0.0
60    CONTINUE
C
```

```
C       CHECK VALUE OF SEAM TONNAGE AND SET MAXIMUM
C
        IF (S7T.GT.2000) S7T=2000
        IF (S8T.GT.2000) S8T=2000
        IF (S9T.GT.2000) S9T=2000
        IF (S10BT.GT.2000) S10BT=2000
        IF (S10AT.GT.2000) S10AT=2000
        IF (S7T.GT.600) IS7=600
        IF (S7T.LT.600) IS7=S7T
        IF (S10AT.GT.200) IS10A=200
        IF (S10AT.LT.200) IS10A=S10AT
C
C       GENERATION OF SEAM COMBINATIONS
C
        DO 600 ISG=140,155
C
C       CALCULATE QUALITIES AND YIELDS FOR ACCEPTABLE TONNAGE COMBINATIONS
C
        SG=FLOAT(ISG)/100.
C
C       CALL QUALITY AND YIELD ROUTINE FOR #7
C
        IS=1
        CALL PERF(IS,AR7,SG,C7,AD7T,PY7,FY7,HY7,Y7)
C
C       CALL QUALITY AND YIELD ROUTINE FOR #8
C
        IS=2
        CALL PERF(IS,AR8,SG,C8,AD8T,PY8,FY8,HY8,Y8)
C
C       CALL QUALITY AND YIELD ROUTINE FOR #9
C
        IS=3
        CALL PERF(IS,AR9,SG,C9,AD9T,PY9,FY9,HY9,Y9)
C
C       CALL QUALITY AND YIELD ROUTINE FOR #10B
C
        IS=4
        CALL PERF(IS,AR10B,SG,CB,AD10BT,PY10B,FY10B,HY10B,Y10B)
C
C       CALL QUALITY AND YIELD ROUTINE FOR #10A
C
        IS=5
        CALL PERF(IS,AR10A,SG,CA,AD10AT,PY10A,FY10A,HY10A,Y10A)
        DO 600 S7=IS7,S7T,100
        DO 600 S8=0,S8T,100
        DO 600 S9=0,S9T,100
        DO 600 S10B=0,S10BT,100
        DO 600 S10A=IS10A,S10AT,100
C
C       CHECK TOTAL OF SEAM TONNAGE
C
        ST=S7+S8+S9+S10B+S10A
        IF (ST.NE.4000) GO TO 600
        IF ((S8+S9).GT.2600) GO TO 600
C
C       TEST QUALITY
C
        AOT=(S7*AD7T+S8*AD8T+S9*AD9T+S10B*AD10BT+S10A*AD10AT)/ST
        IF (AOT.LT.9.40.OR.AOT.GT.9.50) GO TO 600
        P7H=(S7*100.)/ST
        P8H=(S8*100.)/ST
        P9H=(S9*100.)/ST
        P10BH=(S10B*100.)/ST
        P10AH=(S10A*100.)/ST
```

```
C
C       CALCULATE TOTAL HEAVY MEDIA YIELD
C
        HYH=HY7*P7H+HY8*P8H+HY9*P9H+HY10B*P10BH+HY10A*P10AH
C
C       CALCULATE PLANT YIELD AND CORRECT FOR MOISTURE
C
        PYT=PY7*P7H+PY8*P8H+PY9*P9H+PY10B*P10BH+PY10A*P10AH
        PYH=PYT*1.038
        IF (PYH.LT.PY(10))GO TO 600
        HY(10)=HYH
        SGS(10)=SG
        AO(10)=AOT
        P7(10)=P7H
        P8(10)=P8H
        P9(10)=P9H
        P10B(10)=P10BH
        P10A(10)=P10AH
        PY(10)=PYH
        YT=Y7*P7(10)+Y8*P8(10)+Y9*P9(10)+Y10B*P10B(10)+Y10A*P10A(10)
        RE(10)=HY(10)/YT
        CALL SORT(10,PY,AO,P7,P8,P9,P10B,P10A,SGS,HY,RE)
600     CONTINUE
        WRITE(*,650)
650     FORMAT(' ',' #7 #8 #9 #10B #10A SG CC%'
     1  '  HM% YLD% RE'/80('-'))
        WRITE(*,700) (P7(I),P8(I),P9(I),P10B(I),P10A(I),SGS(I),AO(I),
     1  HY(I),PY(I),RE(I),I=1,10)
700     FORMAT(' ',2X,10F7.2)
        STOP
        END
C
C       SUBROUTINE PERF CALCULATES YIELD AND CLEAN COAL ASH FOR SEAMS
C
        SUBROUTINE PERF(IS,RASH,SG,C,AOT,PY,FY,HY,Y)
        REAL*8 C(11)
        REAL NG,HY
        IF (RASH.EQ.0.0) RETURN
        AR=RASH+1.7
        NG=C(1)*EXP(C(2)*SG)
        RE=EXP(-.0002*NG)-(NG/45.)*(NG/45.)*.1
        AO=C(3)*SG-C(4)
C       IF SEAM IS 10B GO TO 5
        IF (IS.EQ.4) GO TO 5
        DM=C(5)-C(6)*ALOG(AO)+C(7)*(AR-C(8))
        GO TO 10
5       DM=C(5)-C(6)*AO+C(7)*(AR-C(8))
10      Y=((AO-2.)/(AR-2.))**DM
        HY=Y*RE
        PY=HY*C(9)+FY*C(10)
        AOT=(AO*HY*C(9)+C(11)*FY*C(10))/PY
        RETURN
        END

C
C       SUBROUTINE SORT
C
        SUBROUTINE SORT(N,A,B,C,D,E,F,G,H,K,L)
        REAL*4 A(N),B(N),C(N),D(N),E(N),F(N),G(N),H(N),K(N),L(N)
50      DO 1500 J=1,N-1
        DO 1000 I=1,N-J
        IF (A(I).GE.A(I+1)) GO TO 1000
        STORE=A(I)
        A(I)=A(I+1)
        A(I+1)=STORE
        STORE=B(I)
```

```
      B(I)=B(I+1)
      B(I+1)=STORE
      STORE=C(I)
      C(I)=C(I+1)
      C(I+1)=STORE
      STORE=D(I)
      D(I)=D(I+1)
      D(I+1)=STORE
      STORE=E(I)
      E(I)=E(I+1)
      E(I+1)=STORE
      STORE=F(I)
      F(I)=F(I+1)
      F(I+1)=STORE
      STORE=G(I)
      G(I)=G(I+1)
      G(I+1)=STORE
      STORE=H(I)
      H(I)=H(I+1)
      H(I+1)=STORE
      STORE=K(I)
      K(I)=K(I+1)
      K(I+1)=STORE
      STORE=L(I)
      L(I)=L(I+1)
      L(I+1)=STORE
 1000 CONTINUE
 1500 CONTINUE
      RETURN
      END
```